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Power spectra of geomagnetic fluctuations between 0.4 and 40 Hz.

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THESIS

POWER SPECTRA OF GEOMAGNETIC FLUCTUATIONS
BETWEEN 0.4 AND 40 Hz

by

Frederick William Clayton

June 1979

Thesis Advisor: O. Heinz

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Power spectra of the fluctuations of the geomagnetic field were obtained for the frequency range of 0.4-40 Hz using an optically pumped Cesium vapor magnetometer. The measurements were made at Monterey, California in May, 1979. The spectra display a gradual decrease in slope at low frequencies with zero slope occurring between approximately 5 Hz and 15 Hz followed by a slight increase in slope. Data was collected at local midnight (0000-0200), local morning (0800-1000) and local afternoon (1600-1800). The morning

and afternoon spectra exhibit what is believed to be a Schumann resonance peak at 8.0 Hz. A peak at 2.2 Hz and its first harmonic (4.4 Hz) were also observed, but are believed to be a man-made phenomenon or a sensor related instrumentation effect. Considerable high frequency disturbances (20-40 Hz) were observed around local midnight and are believed to be ELF "Sferics". A comparison between a magnetically disturbed day (Fredericksburg Index of 7+) and a quiet day (Fredericksburg Index of 2+) at the same time period (0800-1000) showed a difference of 7-9 dB in power spectral density.

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POWER SPECTRA OF GEOMAGNETIC FLUCTUATIONS BETWEEN 0.4 and 40 Hz

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of
the requirements for the degree of

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ABSTRACT

Power spectra of the fluctuations of the geomagnetic field were obtained for the frequency range of 0.4 - 40 Hz using an optically pumped Cesium vapor magnetometer. The measurements were made at Monterey, California in May, 1979. The spectra display a gradual decrease in slope at low frequencies with zero slope occurring between approximately 5 Hz and 15 Hz followed by a slight increase in slope. Data was collected at local midnight (0000-0200), local morning (0800-1000) and local afternoon (1600-1800). The morning and afternoon spectra exhibit what is believed to be a Schumann resonance peak at 8.0 Hz. A peak at 2.2 Hz and its first harmonic (4.4 Hz) were also observed, but are believed to be a man-made phenomenon or a sensor related instrumentation effect. Considerable high frequency disturbances (20-40 Hz) were observed around local midnight and are believed to be ELF "Sferics". A comparison between a magnetically disturbed day (Fredericksburg Index of 7+) and a quiet day (Fredericksburg Index of 2+) at the same time period (0800-1000) showed a difference of 7-9 dB in power spectral density.

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I. INTRODUCTION

This experiment is one phase of a geomagnetic research project currently in progress at the Naval Postgraduate School. The objective of the project is to measure fluctuating electromagnetic fields on the ocean floor in the 10^{-3} to 100 Hz frequency range and to associate the observed phenomena with sources and modes of propagation. The overall project is divided into two main phases: 1) supporting land magnetic field measurements: 2) ocean floor magnetic field measurements. The land data is required for correlation and comparison with the ocean data. The objectives of the measurements reported here are, 1) to collect data on local magnetic field fluctuations at a quiet site in Monterey (La Mesa Village) for comparison with data from the floor of Monterey Bay and, 2) to test the Cesium Vapor magnetometer for the frequencies from .45 Hz to 45 Hz.

The earth's magnetic field consists of a main field, which may be considered constant for our purposes, and a very small (<.1%) time varying component. The main field in Monterey (Geomagnetic Latitude 42.5° N) is approximately 50,000 nT*. It varies on a daily basis by approximately 30-70 nT. The time varying field studied here, with characteristic periods less than 24 hours, is of interest both scientifically and

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* 1 nanotesla (nT) = 10^{-9} Tesla
= 10^{-5} Gauss
= 1 Gamma

from a Naval applications point of view. Applications such as communications, at sea mining, submarine detection and magnetic mines are examples.

Figure 1 shows the general power spectrum of magnetic field disturbances on the earth's surface. This figure also shows the normal magnetic variations (δB) for different frequency ranges. The normal variation in the 0.4 to 40 Hz range is approximately 0.01 to 0.1 nT, which means that power spectral densities of 10^{-2} to 10^{-5} (nT)2/Hz should be expected. These are extremely small variations; i.e., to investigate the time varying field in this frequency range requires that measurements be made to one part in one million of the Main Field.

The data reported here was collected using an optically pumped, Cesium Vapor Magnetometer. The magnetometer sensor had a sensitivity of 0.005 nT and an average system noise of approximately 3×10^{-7} $(nT)^2/Hz$, which allowed for a minimum of 10 dB signal to noise throughout the 0.4 to 40 Hz range. Due to the small field variations to be measured, it was necessary to analyze the data directly on a spectrum analyzer instead of tape recording the signal first since the tape recorder was found to be too noisy. The entire instrumentation configuration and detailed discussion are found in Chapter III.

The results of the experiment met both of the above objectives satisfactorily. The signal to noise ratio was sufficient to extend the data collection to 45 Hz and the use of the

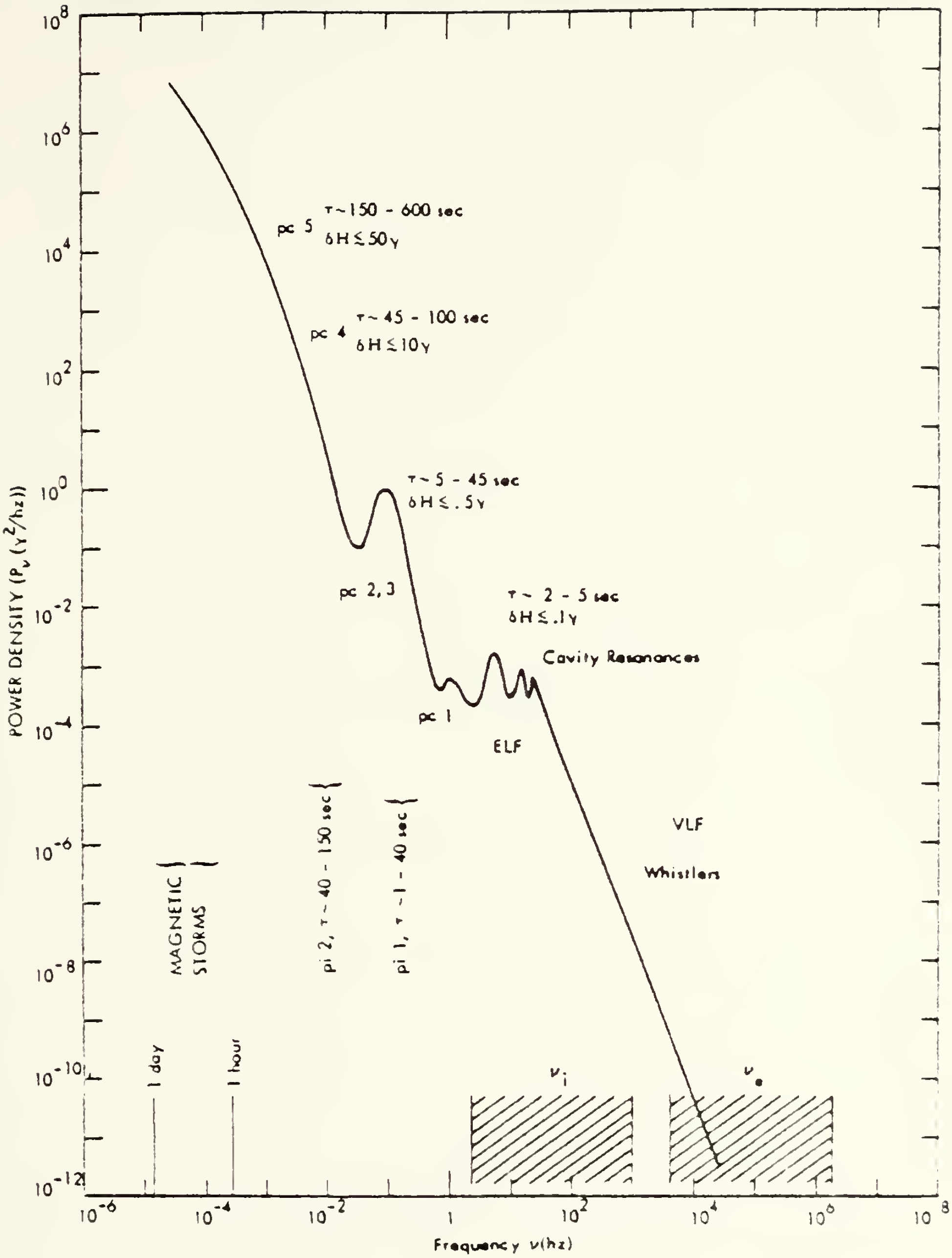


Fig. 1. Power spectrum of geomagnetic disturbances observed on the Earth's surface.

From: [Claudis, Davidson and Newkirk, 1971]

Cesium vapor magnetometer at these higher frequencies was proven to work well, although the instrument was operating close to its lower sensitivity limit (0.005 nT). A more detailed discussion of the conclusions and recommendations is contained in Chapter VI.

II. BACKGROUND

A. GEOMAGNETIC FIELD FLUCTUATIONS

A brief review of the fundamental causes of variations in the earth's magnetic field is provided in this section.

The intensity of the earth's magnetic fluctuations are different for different days. On some days, the changes are smooth and regular; on other days, the changes are irregular because of magnetic disturbances superimposed on smooth variations. The regular smooth traces are called magnetically "quiet" days and the irregular traces are called magnetically "active" or "disturbed" days. There is a world-wide network of magnetic observatories that maintains a continuous record of the time varying field. World Data Center "A" in Boulder, Colorado compiles and issues indices of magnetic activity by observatory location and also provides forecasts of geomagnetic activity on a daily basis.

The average variation patterns derived from chosen quiet day records define a variation field called the Solar Quiet Daily Variation which is denoted by (Sq). Sq varies characteristically with latitude. At the equator the maximum horizontal intensity is 100 nT's where as at higher latitudes it is generally about -25 to -50 nT's. Sq. is also dependent on the season and the phase of the solar cycle. In the summer Sq is increased; in winter it is decreased; and during a sunspot maximum, it is increased. The phase of the moon also

effects daily variations. But this variation, called the "Lunar Daily Variation" (L), is less than 0.1 that of Sq.

Two thirds of these daily (diurnal) fluctuations, i.e., those having a 24 hour period, are due to current sources external to the earth. The remaining one third is due to internal currents induced in the earth's surface layers by variable external fields. The external currents responsible are found to flow at an approximate altitude of 100 kilometers, and are produced by convective movement of charged particles moving across earth's magnetic field lines. The convective motion of the particles is caused mainly by solar heating of the upper atmosphere. In other words, the sun produces a stationary current system in the upper atmosphere, and the earth rotates under it once a day. In Monterey, this effect starts about sunrise and reaches its peak about noon. A normal change of -30 to -70 nT's can be expected at the La Mesa measurement site. This mechanism is known as the Atmospheric Dynamo.

Irregular magnetic fluctuations of one to two hours duration are related to changes in the solar wind pressure on the magnetosphere and associated changes in the southward component of the interplanetary field. These fluctuations are called sudden impulses and magnetic bays. "Sudden Impulses" are sudden increases of several nanoteslas followed by a gradual increase or decrease in the field followed by a return, perhaps with small oscillations, to the normal field. These latter fluctuations usually last about one to two hours.

A very violent time varying magnetic disturbance is that of a magnetic storm. Magnetic storms are caused by plasma bursts from the sun since a solar flare emits both x-rays and plasma. The x-rays precede the plasma and enter the earth's atmosphere causing increased ionization in the sunlit atmosphere. This ionization occurs in the lower ionosphere and enhances the currents in the atmospheric dynamo thereby producing what is known as the Solar Flare Effect, a precursor to magnetic storms.

The major magnetic storm disturbances are caused by dynamic pressure changes of the solar wind. When the plasma blast from the sun arrives it suddenly increases the solar wind pressure, compressing the magnetic field (Sudden Commencement). It maintains the compression for a time, called the initial phase. When the pressure decreases with the passing of the plasma blast, the circulating currents which have been induced in the magnetosphere tend to make the field intensity "overshoot" before the currents gradually dissipate. This initiates the recovery phase back to the normal quiet field condition. The entire magnetic storm can last from one to three days with a recovery times even longer.

Field changes which occur at periods of 0.2 seconds to 10 minutes are called Micropulsations. They characteristically have amplitudes from tens of nanoteslas to a fraction of one nanotesla. Micropulsations are generally divided into two types: continuous (pc) and irregular (pi). The continuous (pc) micropulsations have amplitude variations which are quasi-sinusoidal. These have been classified and are shown

as a function of their oscillation frequency in figure 1. The irregular (pi) micropulsations exhibit irregularities in both frequency and amplitude. Micropulsations below 3 Hz are produced mainly from wave-particle interactions in magnetosphere.

Pulsations of frequencies from 3 to 3000 Hz make up the ELF region of figure 1. This ELF region has three principle contributors: 1) ELF "Sferics": 2) ELF Emissions, 3) Earth-Ionosphere Cavity Resonances.

ELF "sferics" are electromagnetic signals from atmospheric electric discharges that propagate in the earth's waveguide between the ground and the lower boundary of the ionospheric E-Region. The "Sferic" wave travels very long distances and its waveform consists of a main high frequency oscillatory head (VLF), followed by a lower frequency (ELF) tail-like oscillation, sometimes referred to as a "slow tail". "Sferics" commonly last about 20 milliseconds and have frequency components from 30 to several hundred Hertz.

ELF emissions are an excitation of whistler (300 to 30,000 Hz) mode waves by charged particles streaming along the earths main field lines. The whistlers in the VLF region sometimes produce lower frequency components in the ELF region.

The Cavity Resonance signals are resonantly excited by lightning transients in the concentric shperical cavity between the earths surface and the lower region of the ionosphere. The power spectra of the signals show maxima near 7.8, 14.1, 20.3, 26.4 and 32.5 Hertz.

B. PREVIOUS WORK

Previous work by Santirocco and Parker [1963] and Parker [1964] indicates that the geomagnetic field decreases with a slope of approximately -6 dB/octave between 10^{-4} and 1 Hz. From 1 to 40 Hz, the field exhibits a leveling off and is dominated by the Schumann Resonances [Schumann and König, 1954]. At about 80 Hz the sharp decrease in slope resumes. Measurements of the main field made by Campbell [1966] indicated a general increase between 20 and 70 Hz. However other spectra [Larsen and Egelund, 1968], indicate that the general background field decline of -6 dB/octave continues through the frequency range of 5 Hz to 70 Hz with the Schumann resonance activity superimposed on the declining background. If this is the case, there is a 6 dB/octave decline in the power spectra over a six decade frequency range.

More recent measurements in the frequency range of 0.1-14 Hz were conducted by A.C. Fraser-Smith and J.L. Buxton [1975]. Their measurements were taken over a two month interval at Stanford, California which is close to Monterey, California. They found that the general decline in the slope (-6 dB/octave) continued to approximately 5 Hz, where the decline was arrested by the Schumann resonances. Their results also clearly indicated the first Schumann resonance at approximately 8 Hz.

Most previous work was done in the low frequency ranges including recent work at La Mesa in Monterey, [Barry 1978], covering the frequency region from 0.1 Hz to 10 Hz. The

present experiment was conducted as a follow-on project to extend the data into higher frequency ranges and overlap previous work for correlation purposes.

C. USE OF CS VAPOR MAGNETOMETER AT HIGHER FREQUENCIES

The previous measurement system used by Barry [1978] was designed for geomagnetic exploration. A filter in the output circuit reduced the frequency response above 2 Hz and was modified to increase its output response to 100 Hz as discussed in Appendix A. This systems signal-to-noise ratio was subsequently proven to be too small for accurate analysis of the geomagnetic field between 0.4 and 40 Hz. However, the sensor specifications stated it was not limited in freqquency range or minimum sensitivity (0.005 nT). Since magnetic signals on the order of 0.1 to 0.01 nTs were expected, a second experimental objective was to prove the use of the CS vapor magnetometer between 0.4 to 40 Hz. The sensor was then connected to the measurement system used for ocean floor magnetic field measurements. The magnetometer was shown to be capable of measurement throughout the above range even on magnetically very quiet days (<2+ Fredericksburg Index). A detailed discussion of tests and results is contained in Chapters IV and V.

III. EXPERIMENTAL SETUP

A. LAYOUT OF EXPERIMENT

The measurement of the field variations was carried out with a Cesium vapor, optically pumped magnetometer. The sensor and sensor electronics were located in a glass sphere placed on the ground 48 meters (160 ft.) from NPS, Bldg. 318 (latitude: 36°36', longitude: 122.3° W) where the power supply equipment and other electronics were installed. The system outline is shown in figure 2.

The time varying geomagnetic field was recorded during three time intervals: 0000-0200, 0800-1000 and 1600-1800 local time. Published magnetic activity indices varied from 2+ to 7+ (Fredericksburg Index) during the course of the experiment.

B. DATA COLLECTION SYSTEM

The system, illustrated in figure 2 has the following major components:

1) Cesium Vapor Sensor (Varian Model 4938)
2) Sensor Electronics (Varian Model 4938)
3) Sensor Coupler (Varian Model 49-617C)
4) Discriminator - Frequency to DC Voltage (Anadex P-375)
5) Differential Amplifier (TEKTRONIC AM-502)
6) BANDPASS FILTER (KROHN-HITE 3750)
7) 24 Volt Battery or Alternate DC Power Source
8) Spectrum Analyzer (Schlumberger 1510)

The sensor generates a signal whose frequency is

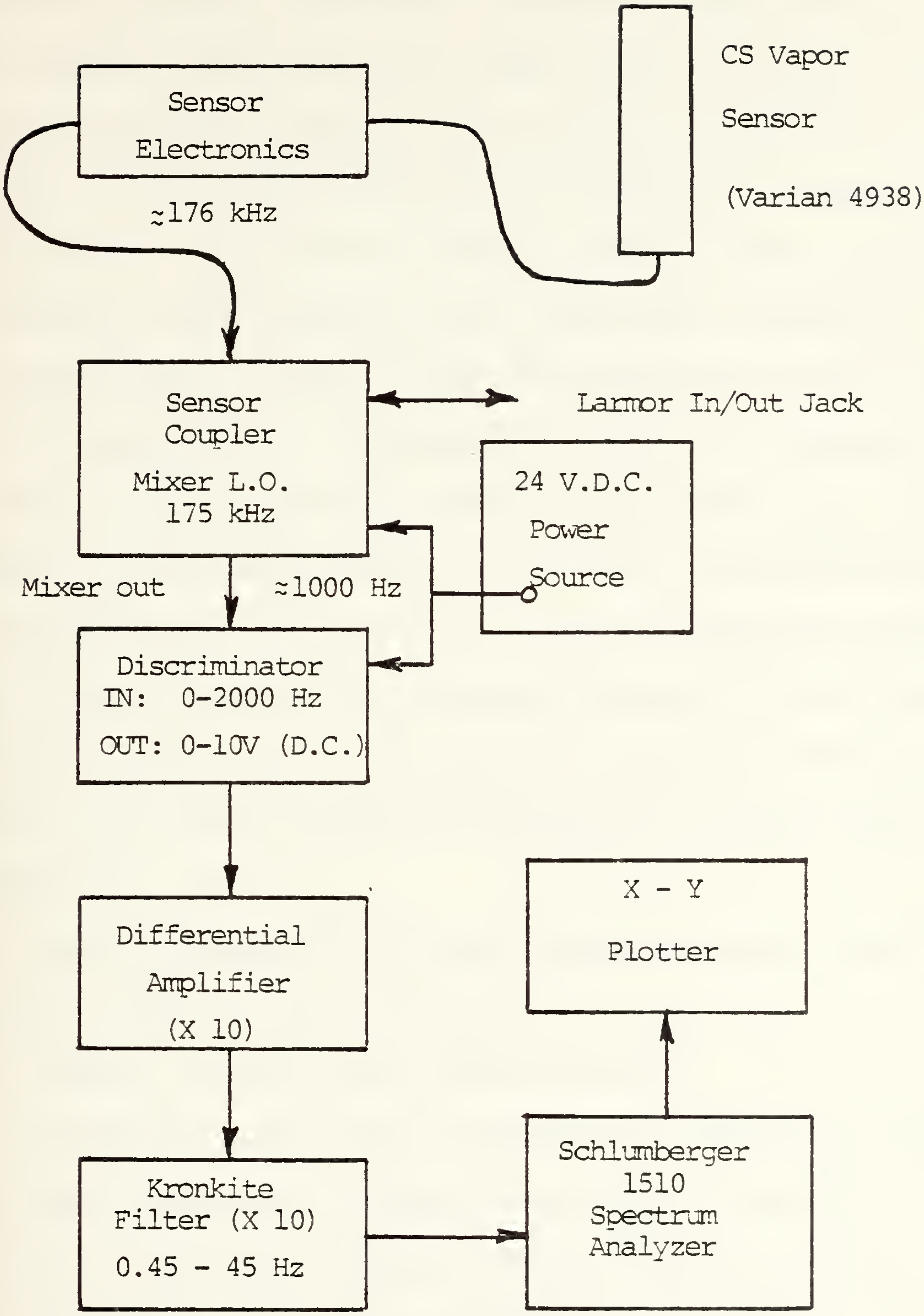


Figure 2

Measurement System Configuration

proportional to the ambient magnetic field intensity. This frequency is called the Larmor frequency. The Larmor frequency signal (≈176 kHz) is transmitted via coaxial cable to the sensor coupler, where it is mixed with a 175 kHz crystal oscillator signal and generates a difference frequency between 0 and 2000 Hz. This mixer output is sent to the input of the discriminator which converts the difference frequency to a dc voltage output (0-10V). The discriminator output is thus directly proportional to changes in the earth's magnetic field. The discriminator output is amplified and sent to an adjustable bandpass filter (KROHN-HITE Model 3750). The filter had a 20 dB gain between 0.45 and 45 Hz and a 24 dB/octave roll-off beyond the pass band. The amplified output is then sent to the Spectrum Analyzer. The spectrum analyzer output was plotted in hard copy on the X-Y Plotter for data reduction and analysis.

The system components and individual component settings are discussed in the following subsections:

1) Sensor - Cesium Vapor Magnetometer.

The sensor acts like an oscillator which produces a signal whose frequency, (Larmor Frequency) is directly proportional to the total magnetic field intensity in which the sensor operates. This proportionality is a direct result of the Zeeman splitting of the energy levels of the Cesium valence electron in a magnetic field. The energy levels have a known number of sublevels whose energy differences are proportional to the intensity of the external magnetic field. The separation in energy (ΔE) between these Zeeman levels can be

calculated by measuring the frequency (ν) of the emitted or absorbed photons ($E = h\nu$). But ΔE is directly proportional to the external (ambient) magnetic field B by the equation

$$\Delta E = \frac{g\ e\ h}{4\pi m}\ B \qquad \text{(JOULES)}$$

where g = Lande g factor

e = charge on the electron

h = Planks' constant

m = mass of the electron

B = magnetic field

Therefore, by monitoring or measuring ν, the changes in the magnetic field intensity can be measured via a proportionality constant. A more detailed description of the optically pumped magnetometer is given in Barry [1978] and Bloom [1961].

The sensor used in this experiment had the following pertinent characteristics:

a) Sensor output proportionality constant for Cesium = 3.499 Hz/nT.

b) Sensitivity = 5 picotesla

c) Range: Continous from 20,000 - 80,000 nT

d) Nominal Field Frequency $\approx$176200 Hz (Corresponds to 50357 nT)

The sensor was securely fastened inside a glass sphere with its electronics package. The sphere was sealed and placed into a non-magnetic plastic covering and holding device which allowed the whole assembly to be placed flat on the ground with the sensor aligned vertically. The vertical alignment

was within the 45° optimum operating cone of the sensor. The sensor was connected and powered by 48 meters of coaxial cable to the other components of the system in Bldg. 318.

2) Sensor Coupler

The sensor couplers purpose was to provide power to the sensor and the sensor electronics package and detect the Larmor frequency from the sensor. The coupler used in this experiment had a reference crystal oscillator as a mixer with a frequency of 175 kHz. The mixer output signal was a sine wave with a frequency equal to the difference between the Larmor frequency and the reference oscillator. The output of the mixer was the input to the discriminator. The difference frequency was normally between 1000 and 1500 Hz, which was in the middle of the linear dynamic range of the discriminator. The sensor coupler was powered with 24 VDC from a PMC AC/DC power supply.

3) Discriminator (ANADEX PI-375)

The discriminator was a 24 VDC powered Anadex Frequency to DC converter with the following characteristics:

a) Input frequency range 0 - 2000 Hz

b) Output DC voltage 0 - 10V full scale

c) Power 22 - 30 VDC

d) Common Mode Rejection 60 dB at 60 Hz

The output of the mixer was connected to the discriminator. Therefore, a change in magnetic field intensity was converted to a voltage whose amplitude was proportional to the magnetic field changes. Laboratory testing resulted in a sensor-coupler-discriminator sensitivity calibration of 17.2 mV/nT.

Since the changes in magnetic field in the frequency range of 1 Hz to 40 Hz were approximately 0.01 nT; it was necessary to amplify the discriminator output prior to further analysis.

4) Differential Amplifier (TEKTRONIC AM-502)

The output of the discriminator was connected to a single input of the differential amplifier. The other input was grounded. The amplifier was operated in the DC offset mode with an upper cutoff frequency of 100 Hz. The DC offset allowed for removal of the DC component of the discriminator signal. The amplification factor used for this experiment was 10.

5) BANDPASS FILTER (KROHN-HITE Model 3750)

The amplified output of the differential amplifier was connected to an adjustable bandpass filter. The filter included a 20 dB amplifier stage used to further amplify the signal. The bandpass mode was utilized to reject high power signals present below 0.45 and to reduce the 60 Hz interference to an acceptable level. The bandpass chosen for this experiment was 0.45 to 45 Hz with 24 dB/octave slope above and below the set frequencies. This bandpass allowed the actual signal level from 0.5 to 45 Hz to be amplified above the noise to an acceptable level (10 dB) without overdriving the dynamic range of the Spectrum Analyzer. The output of the Bandpass filter was sent directly into the Spectrum Analyzer discussed below.

C. DATA ANALYSIS SYSTEM

The data was analyzed directly from the output of the

bandpass filter by the Schlumberger Model 1510-03 Spectrum Analyzer and plotted in spectral form by a Hewlett Packard X-Y Plotter. The Spectrum Analyzer is explained in detail below. The X-Y Plotter was used only as a hard copy device and recorded each spectrum used in the experiment.

1) Schlumberger Model 1510-03 Spectrum Analyzer

The spectrum analyzer is a fully digitized fourier transform instrument, converting time domain signals into the frequency domain with excellent resolution providing a real time spectrum component analysis of analog or digital input signals in 256 spectral bins across one of 10 selectable frequency ranges. The Cathode Ray Tube displays the results as a dot showing magnitude of power and frequency. The resolution is dependent on the frequency range selected. The operator can select the number of averages desired up to a maximum of 1024 individual spectra.

The anlayzer has an option of two window functions, Rectangular and Hanning Window. The window function amplitude modulates the analysis sequency in each digital bin. The window function for the Rectangular window is unity while the Hanning function is:

$$\frac{1}{2} - \frac{1}{2} \cos 2\pi \left[\frac{n - \frac{1}{2}}{1024}\right]$$

for each n of the 1 to 1024 data samples. The Hanning window was selected because it has lower side lobes for each spectral bin thereby reducing the amount of interference influence from one bin on another. This was particularly important in the case of the 60 Hz interference reduction.

IV. SYSTEM CALIBRATION TESTS AND RESULTS

A. SYSTEM TESTS (LA MESA SITE)

The tests to be conducted prior to data collection were:

1) System Noise Measurement Test

2) System Signal to Noise Verification

3) System Frequency Response Test

The first test was to obtain a System Noise Measurement for all the components in the system except the sensor and sensor electronics.

This was accomplished by substituting for the sensor and its electronics a frequency synthesizer (General Radio Type 1163A). It is extremely important to use a crystal controlled type frequency synthesizer because it is necessary to have stabilities in the range of 1 part in 10^8 Hz. Anything less stable adds noise to the system.

The test was conducted with the frequency synthesizer set at 176400 Hz, very close to the typical magnetic field frequency signal. This signal was applied to the "Larmor Out" jack on the back of the Varian sensor coupler and beat against the internal mixer reference oscillator.

Since the frequency synthesizer was a constant frequency, the output of the mixer was a constant frequency and the discriminator should have a constant DC level output. Therefore, any noise generated within the system will be measured as small changes by spectrum analyzer and displayed.

The first series of test results concluded that the 60 Hz signal was more than 50 dB above expected data and was still overdriving the analysis equipment (see figure 3). There was only a 3 to 7 dB average signal-to-noise ratio above 60 Hz which was deemed unacceptable. Therefore, the KROHN-HITE filter was used in the bandpass mode to reduce the 60 Hz interference on the high end. The filter was also used to reduce the high spectral power density of the actual signal on the low end (<0.5 Hz) so that the small fluctuations at intermediate frequencies could be amplified properly without exceeding the dynamic range of the system. The final filter setting of 0.45 Hz to 45 Hz was chosen and the test conducted again, this time with acceptable results. The same system noise test was conducted several times during the course of the experiment with extremely close repeatability. The average system noise spectrum is illustrated in figure 4. It should be noted that the system noise is approximately 10 dB below the minimum expected signal in the selected frequency range.

The system signal-to-noise verification test was run immediately following the noise test by disconnecting the frequency synthesizer and connecting the magnetometer sensor and its electronics to the sensor coupler. The power spectrum was obtained on the Spectrum Analyzer with everything in the system at the same settings. The power spectrum obtained is also shown on figure 4. It is evident that the signal-to-noise ratio is approximately 10 dB. This means that the

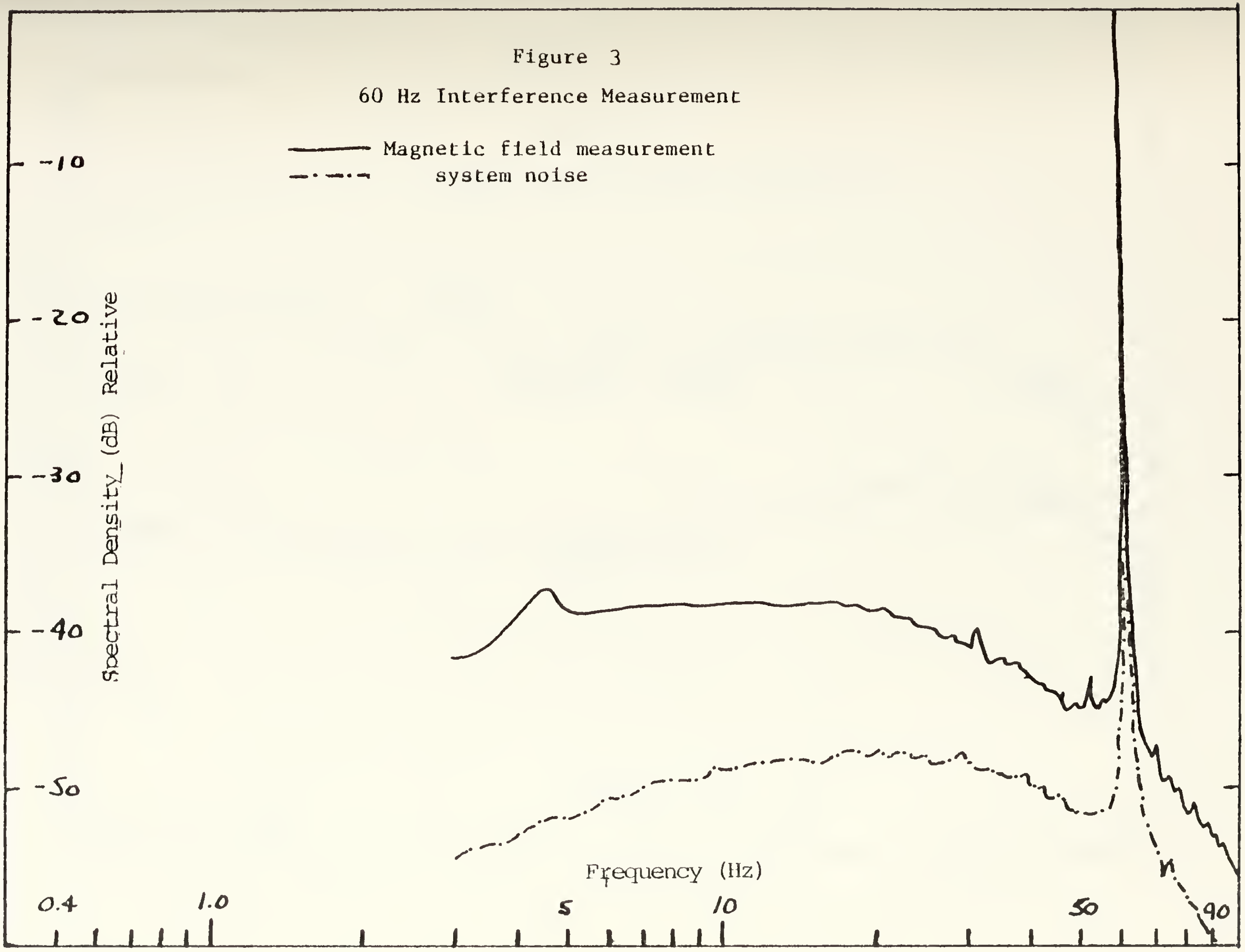
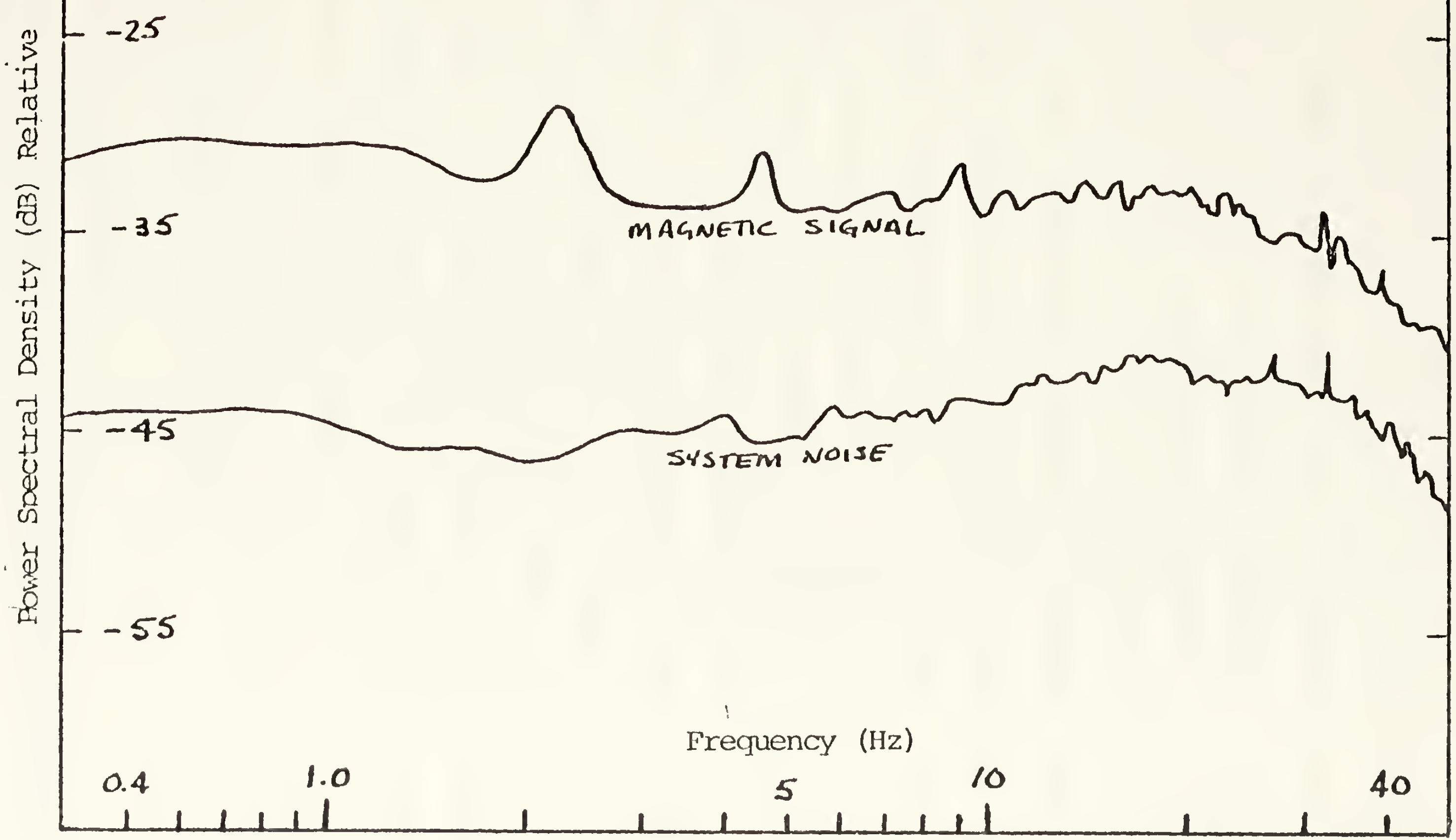


Figure 3

60 Hz Interference Measurement

Figure 4

System Signal-To-Noise Verification



actual signal is just far enough above the present systems noise floor to take meaningful data over the frequency range from 0.4 Hz to 40 Hz. The signal-to-noise ratio from 40 Hz to 50 Hz is only 3 to 5 dB which is marginal.

The last important test to be conducted prior to data collection was a frequency response test. This test was conducted using the same settings on all system equipment. The sensor was disconnected and the system was connected to a FM function generator (I.E.C. Model F-35) set at 176 kHz at a known amplitude. A sine wave sweep generator (WAVETEK Model 134), connected to the input of the FM function generator, was used to generate test frequencies from 0.4 to 100 Hz. The Spectrum Analyzer was then used to record the level of each frequency generated to determine the system's frequency response. Figure 5 shows the results of this test normalized to 0 dB. In general: 1) the low end of the spectrum is down 10 dB at frequencies below 0.8 Hz because of the bandpass low cutoff filter setting of 0.45 Hz; 2) the mid range from 0.8 Hz to 20 Hz is essentially flat, 3) the range from 20 to 45 Hz begins to fall off due to the filters in the discriminator, and 4) the region between 45 and 50 Hz is down 19 dB at 50 Hz due to a combination of the discriminator filters and the KROHN-HITE bandpass high frequency cutoff filter.

B. SUMMARY OF TEST RESULTS

The important parameters and operating characteristics are summarized below:

1) An acceptable signal-to-noise ratio of 10 dB was

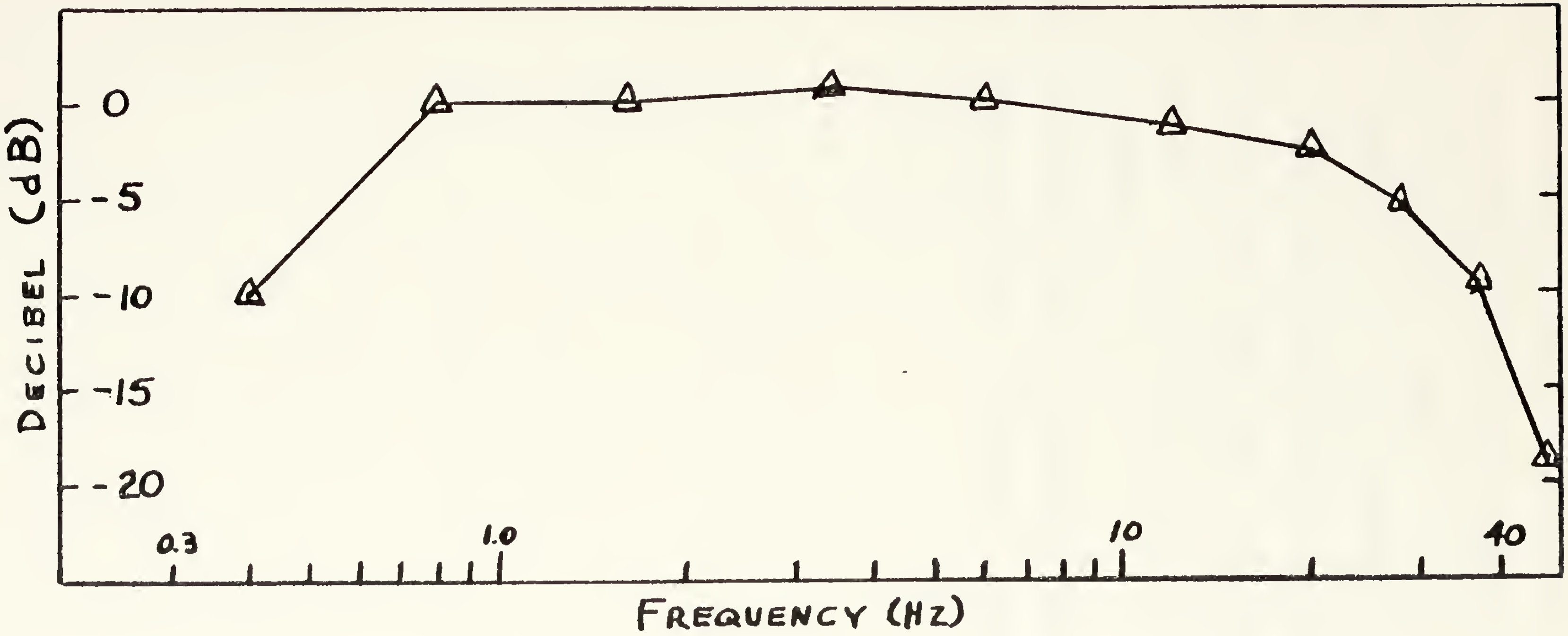


Figure 5. System Frequency Response Curve

obtained in the frequency range between 0.4 Hz and 40 Hz. Therefore the frequency range on the spectrum analyzer of 0.2 to 51.2 was selected for data collection.

2) It was necessary to operate the KROHN-HITE filter in the bandpass mode between 0.45 Hz and 45 Hz to eliminate the major 60 Hz interference above 45 Hz and eliminate actual signal high power level below 1 Hz. This was necessary to maintain the Spectrum Analyzer in range and maintain a 10 dB minimum signal-to-noise ratio.

3) Measured sensitivity of discriminator is 17.2 mV/nT.

4) The System frequency response is known and correctable from 0.4 Hz to 40 Hz.

V. EXPERIMENTAL RESULTS

A. INTRODUCTION

During the month of May 1979, a total of 90 hours of data was analyzed covering three specific time intervals during each day; 0000-0200; 0800-1000; 1600-1800. Each data period was 85 minutes long from which 1024 individual spectra were computed and averaged. The width of each frequency bin was 0.2 Hz (256 bins between 0.2 and 51.2 Hz). The statistical characteristics result in a 95 percent confidence that the estimate will be within a 0.2 dB accuracy.

Comparisons were made of the power spectral density for each of the above time frames for a number of days. Comparisons were also made for spectra at different times of the day to determine daily variations. The data was correlated with previous data, [Barry, 1978; and Frasier-Buxton, 1975] at 1 Hz to show compatability for each time period using quiet days selected from the data. The days of varying degrees of magnetic activity were investigated separately.

B. MAGNETIC SPECTRA (LA MESA SITE)

The data presented in the following figures are of typical spectra during a very quiet period of magnetic activity, (2+ Fredericksburg Activity Index). On only one occasion did the magnetic activity index exceed four for more than one activity index period (three hours). This was caused by a solar "Short Shot", or very fast increase in the solar wind, followed by

a fast passing of the plasma pulse and the solar wind returning to normal. The Fredericksburg and the Boulder observatories recorded a 7+ index on 29 May 1979 followed by two days of unsettled activity due to oscillations of the magnetosphere.

Figure 6 through 8 represent typical spectra for the daily field variations during the 0000-0200, 0800-1000 and 1600-1800 time periods. These typical spectra were analyzed during a very quiet period when the Fredericksburg index was 2+. The 0000-0200 time period spectra indicate a disturbed region from approximately 20 to 40 Hz with significant (>3 dB) frequency peaks at 2.2 and 4.4 Hz. The 0800-1000 typical spectrum was very quiet in the 20 to 40 Hz region. It also had frequency peaks at 2.2 and 4.4 Hz and additional peaks at approximately 8 Hz and 30.8 Hz. The 1600-1800 spectrum indicates a slightly disturbed frequency range from 20 to 40 Hz with additional peaks at 2.2, 4.4 and 8 Hz.

Figure 9 through 11 show four individual spectra of each local time period and include the days of maximum disturbances to show the full range of variations during the period of observations.

Figure 12 through 14 are averages of six individual, 85 minute data runs on quiet days when the Fredericksburg Index was 2+ or less. These averages were plotted for local midnight, (0000-0200), morning (0800-1000) and afternoon (1600-1800) curves. They indicate the same representative peaks seen in the typical spectra for the same time period except that the 30.8 Hz peak is seen in all curves instead of just the 0800-1000 time period by using quiet days for averaging.

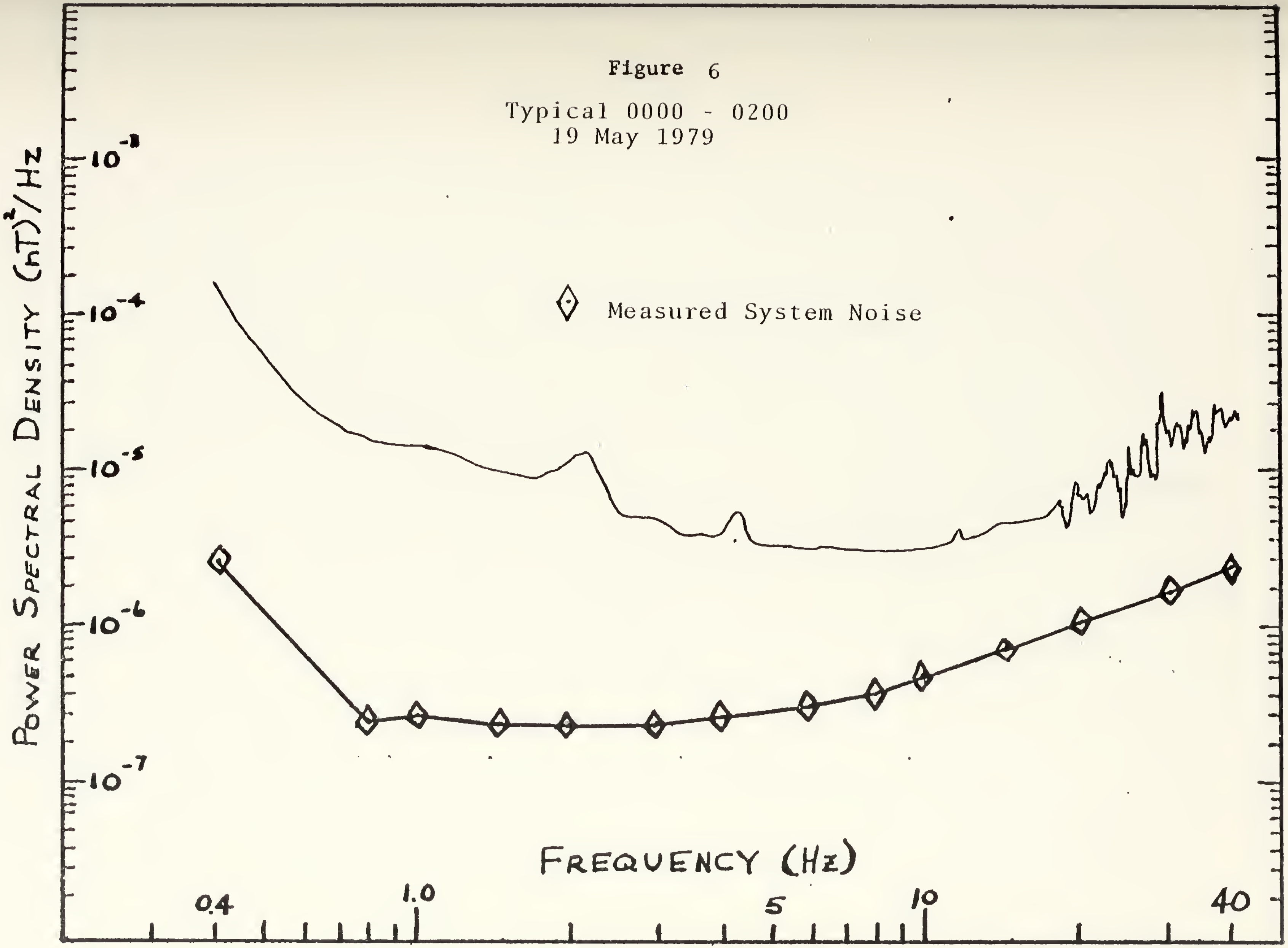


Figure 6

Typical 0000 - 0200
19 May 1979

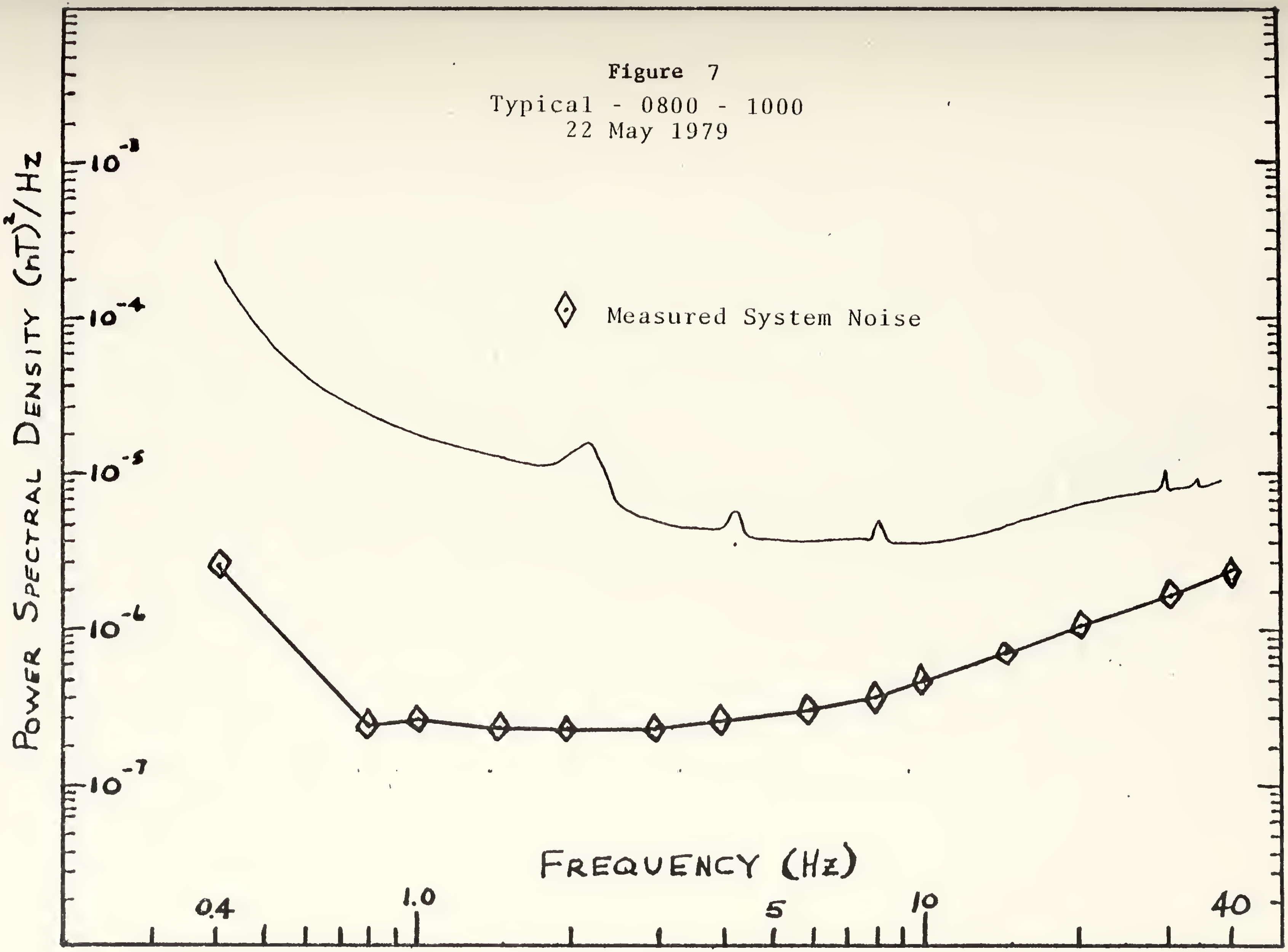


Figure 7

Typical - 0800 - 1000
22 May 1979

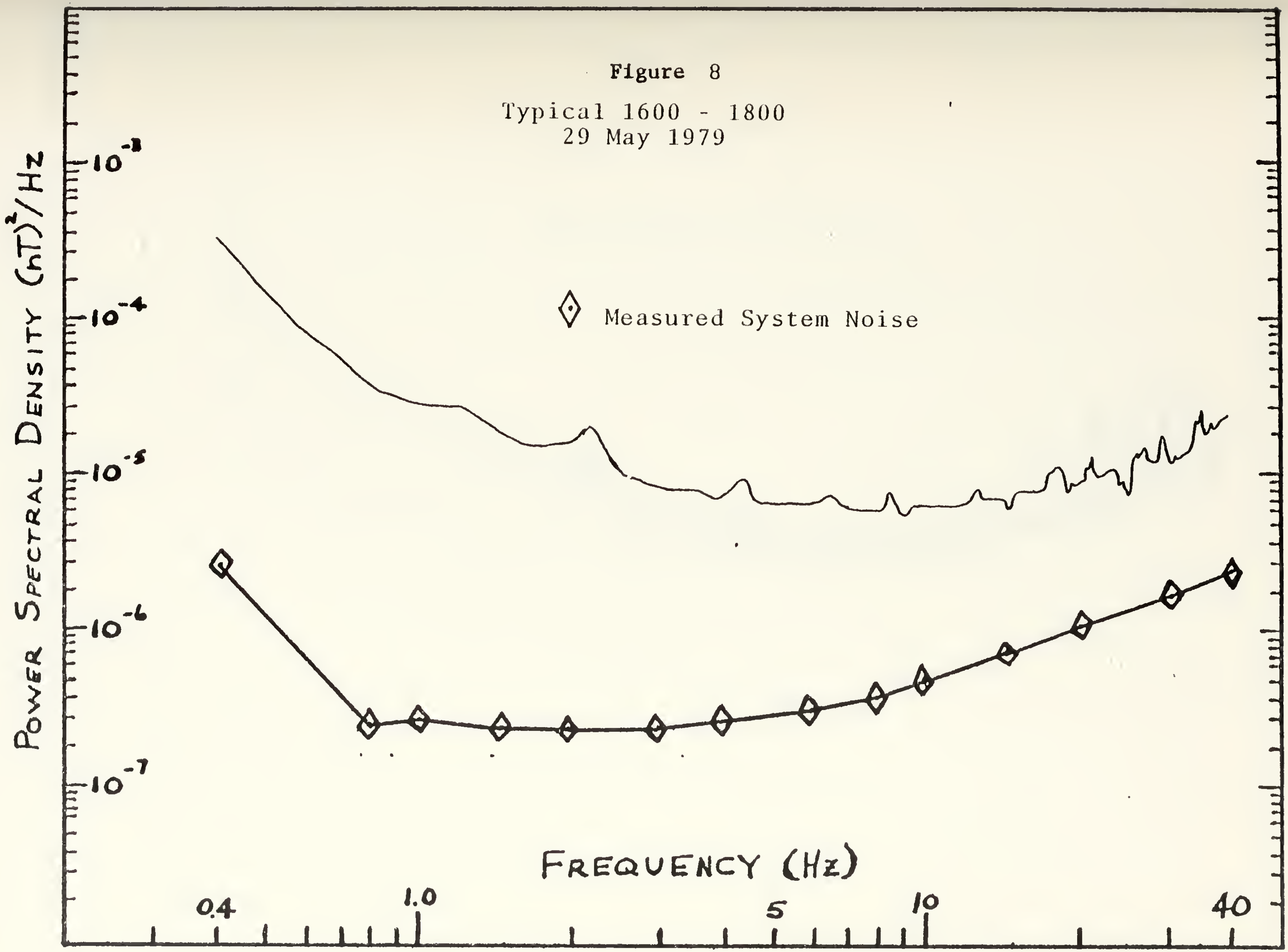


Figure 8

Typical 1600 - 1800
29 May 1979

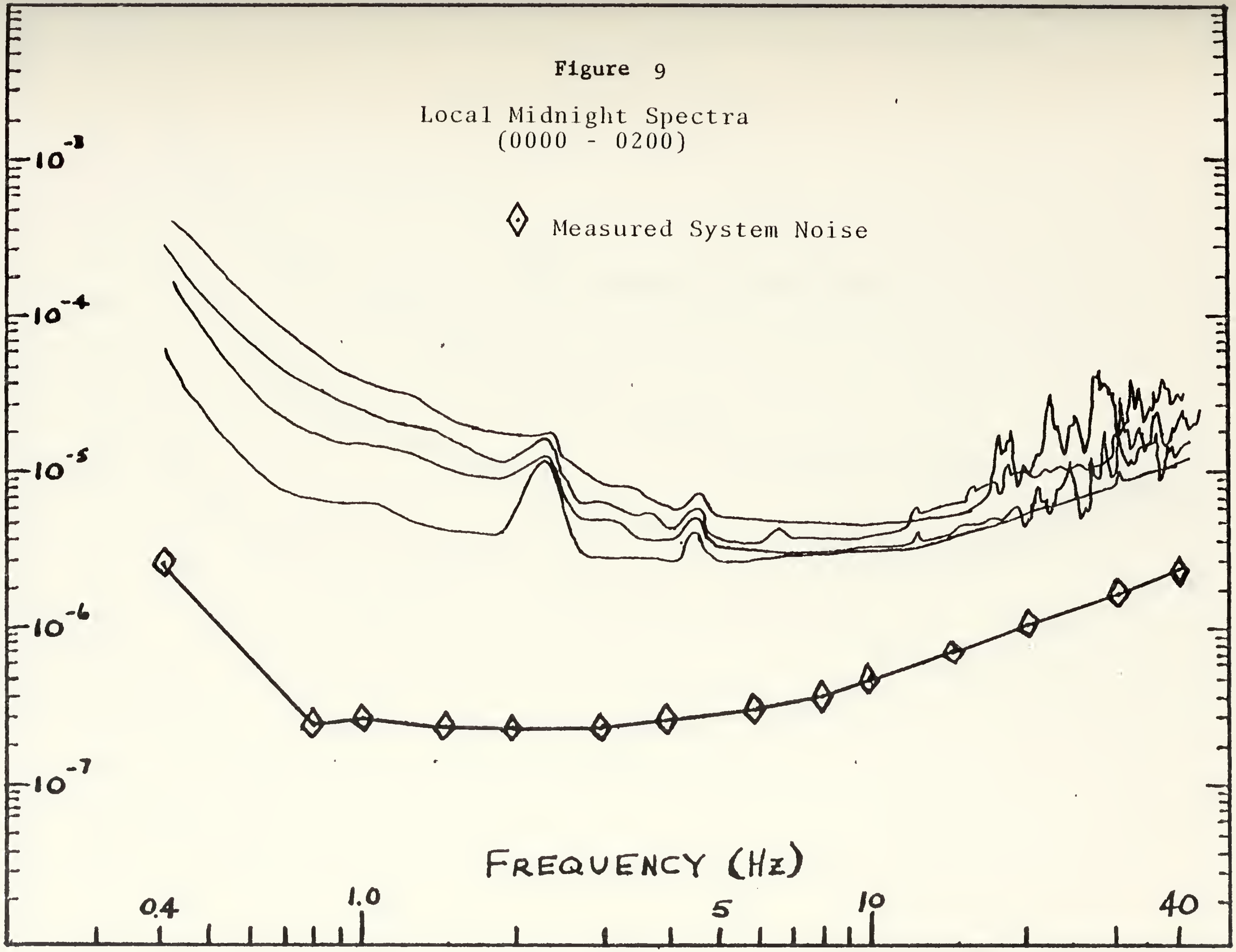


Figure 9
Local Midnight Spectra
(0000 - 0200)
Measured System Noise
POWER SPECTRAL DENSITY (nT)²/Hz
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
FREQUENCY (Hz)
0.4
1.0
5
10
40

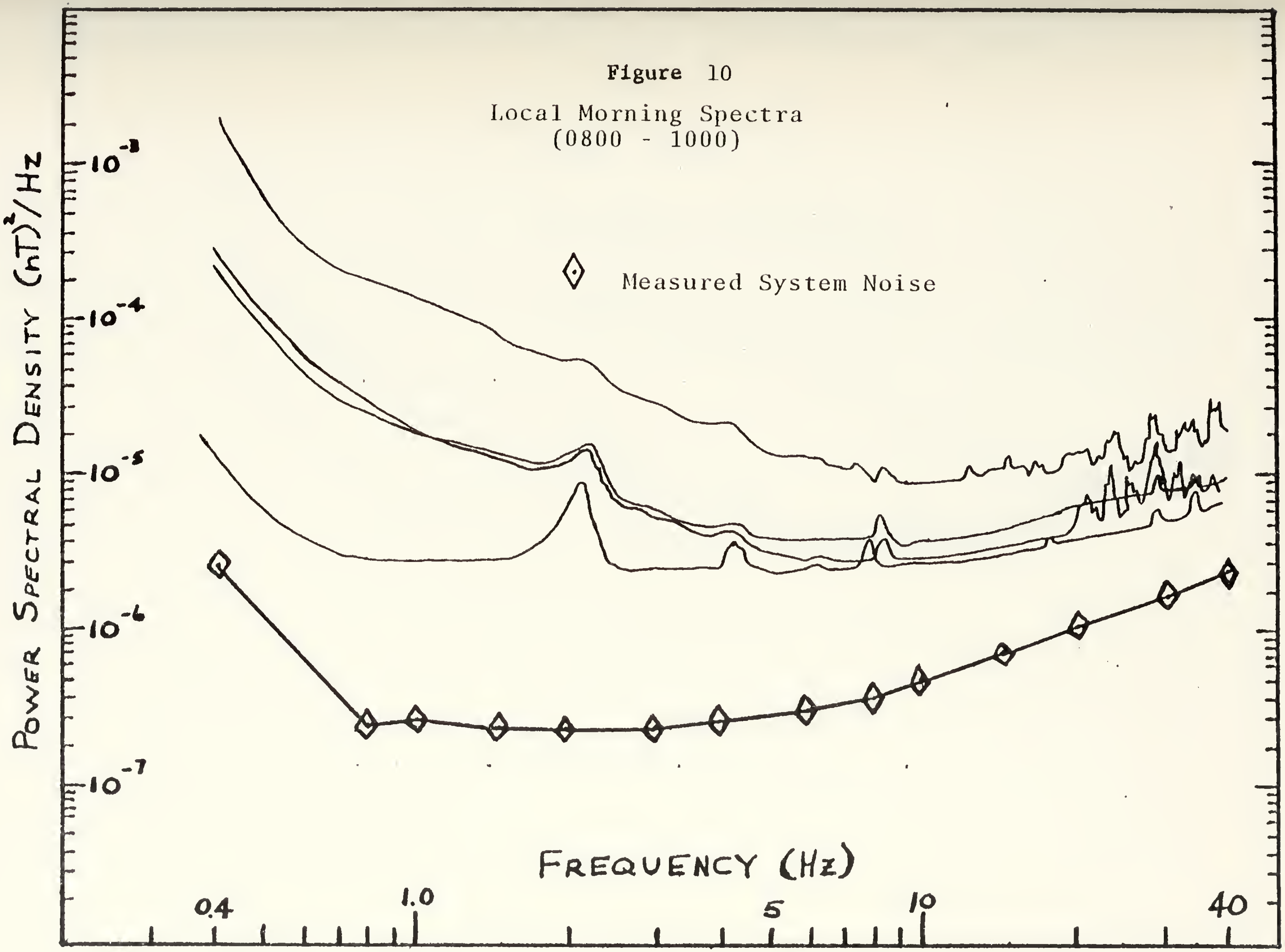


Figure 10

Local Morning Spectra
(0800 - 1000)

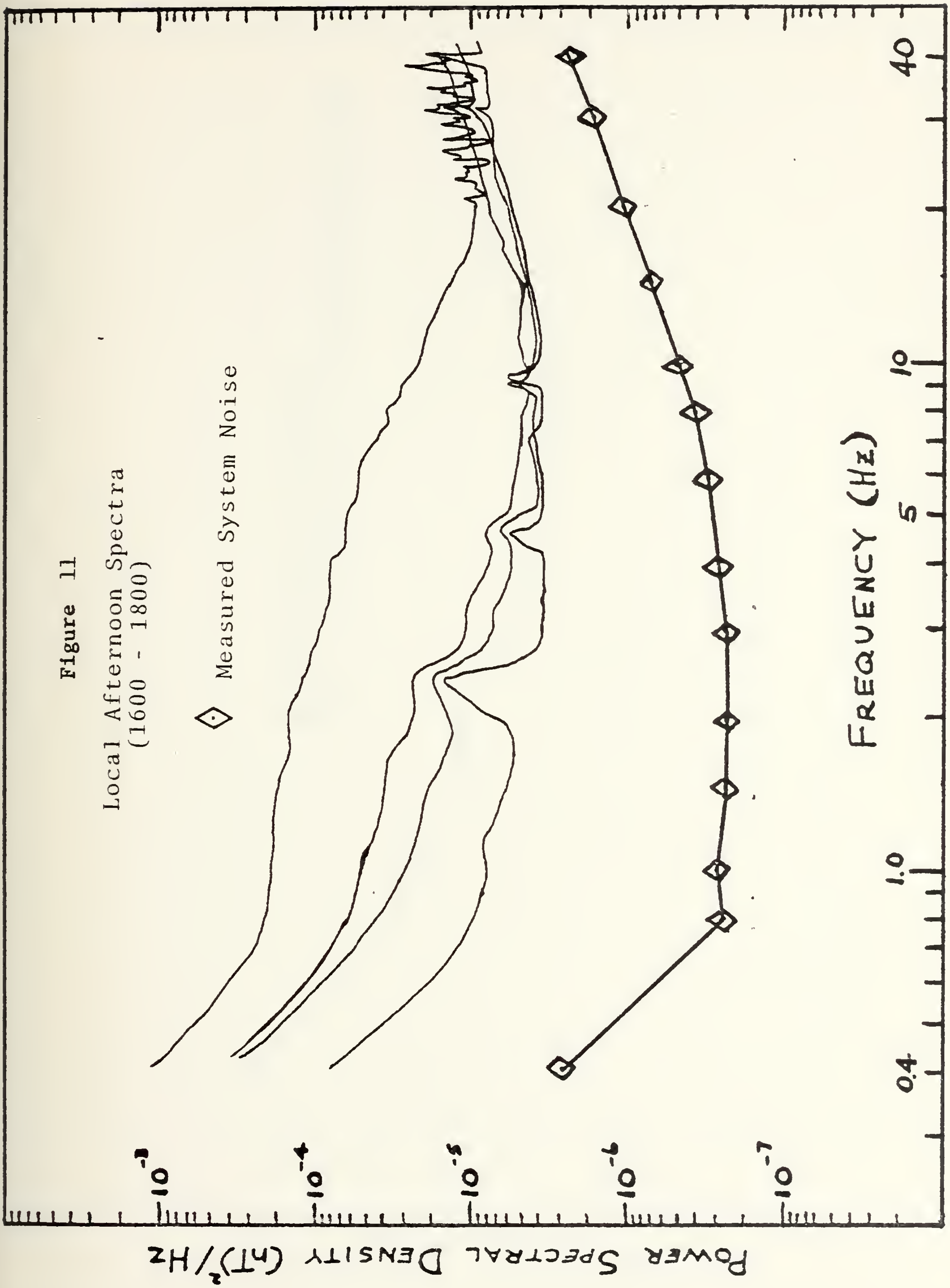


Figure 11
Local Afternoon Spectra
(1600 - 1800)
◇ Measured System Noise
FREQUENCY (Hz)
0.4
1.0
5
10
40
POWER SPECTRAL DENSITY (nT)²/Hz
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}

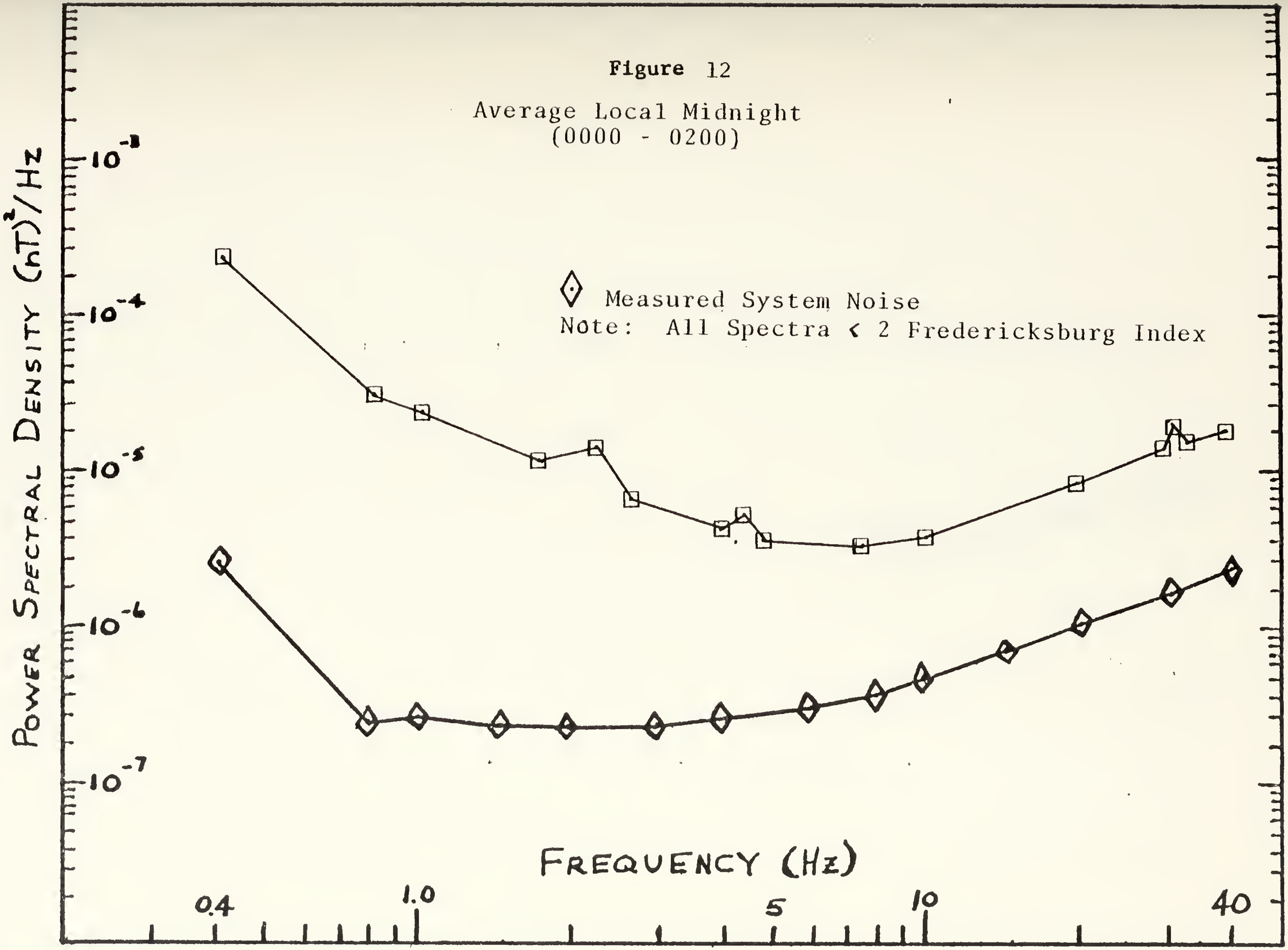
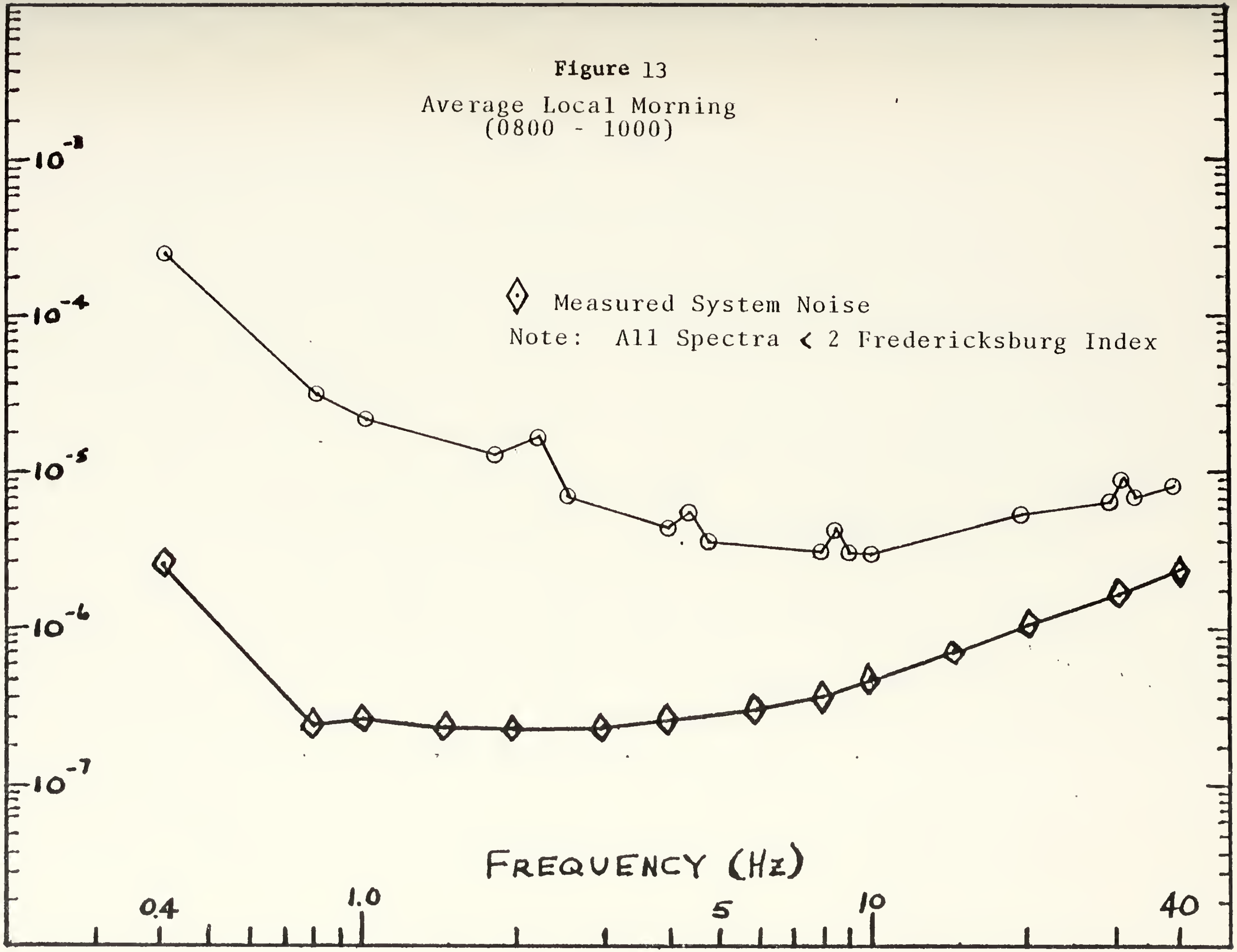


Figure 12

Average Local Midnight
(0000 - 0200)

Figure 13

Average Local Morning
(0800 - 1000)



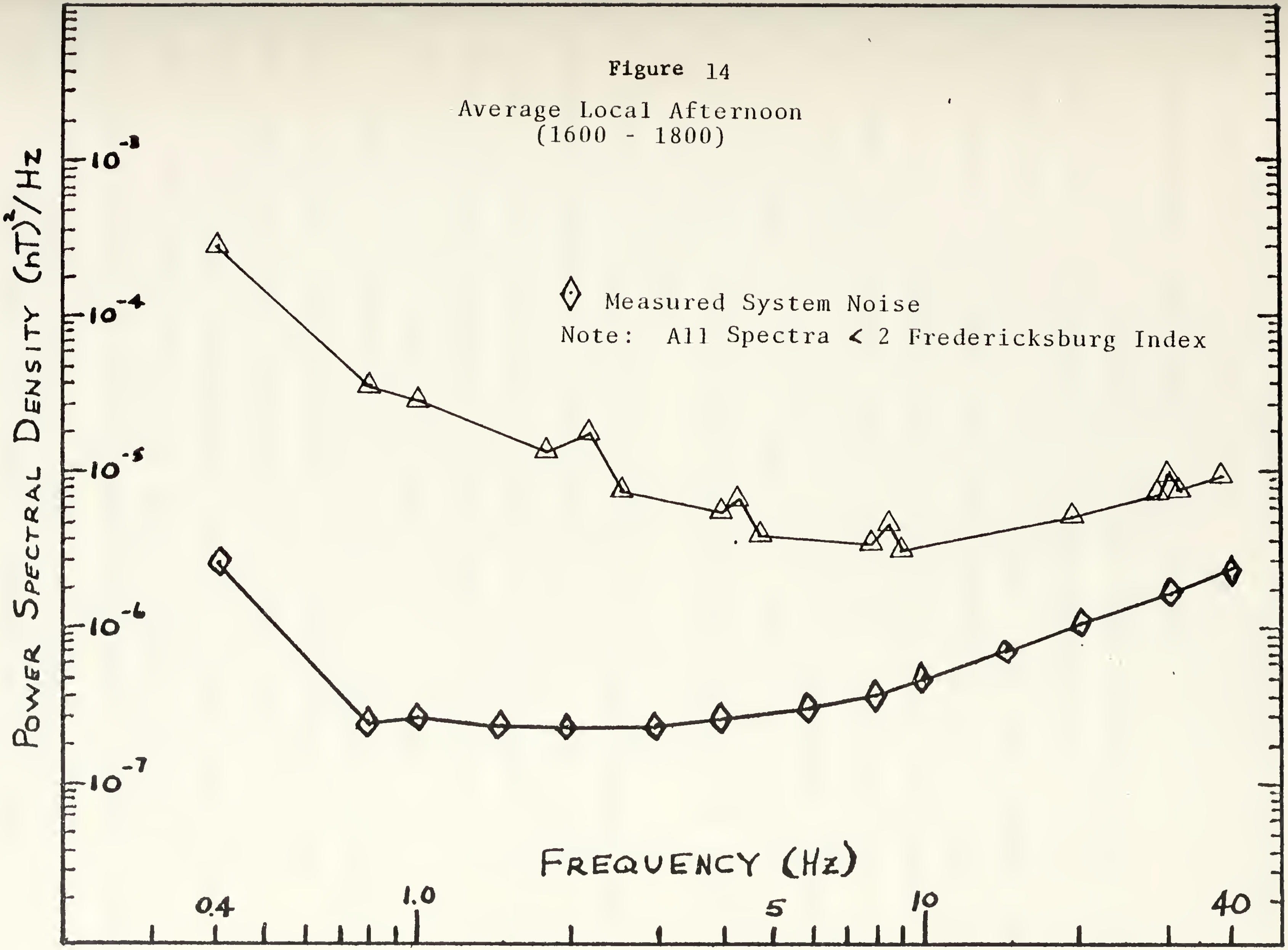


Figure 14

Average Local Afternoon
(1600 - 1800)

The 30.8 Hz peak was also seen in the system noise curve (figure 4), and it was therefore, concluded that this peak was the result of system noise. (It was deleted from the system noise curves seen on each figure.)

Figure 15 is a composite of the local averages which includes all the average local time periods on one curve for comparison purposes. All the average local time periods are very nearly the same at the low frequencies with a signal-to-noise ratio of approximately 15 to 20 dB. The individual averages vary slightly above 10 Hz with a signal-to-noise ratio of 4 dB at 40 Hz. A nominal value of the composite spectra at 1.0 Hz was 2.6×10^{-5} $(nT)^2/Hz$. The local midnight (0000-0200) average did not show the 8 Hz peak seen in the other two local averages.

Figure 16 shows a quiet day (2+ on Fredericksburg Index) versus a magnetically disturbed day (7+ on Fredericksburg Index) at the 0800-1000 time period. The disturbed day indicates increased magnetic activity above 10 Hz and an overall increase in power spectral density of 7 to 9 dB.

Figures 17 through 19 are included to demonstrate changes during a small magnetic storm, (7+ Fredericksburg Index). The small storm was indicated on May 29, 1979 and created observed magnetic disturbances on the 30th and 31st of May 1979. The maximum changes in power spectra density illustrated in figure 17 reveals a maximum change in power density of 13 dB at about 2 Hz. At 1 Hz, the difference was 11 dB while the difference diminished to approximately 2 dB at 20 Hz. Figures 18 and 19 show the effects of the power density for

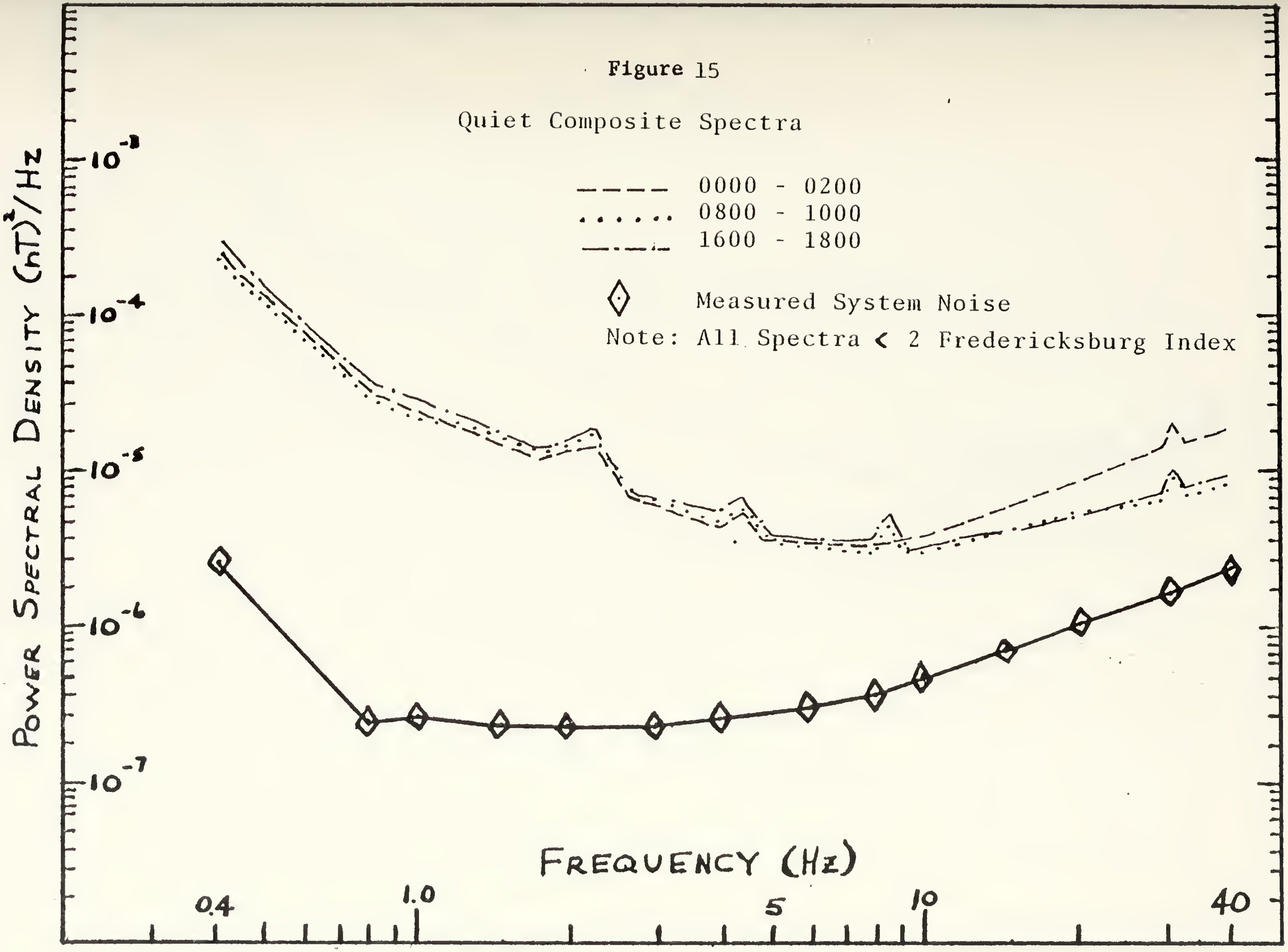

Quiet Composite Spectra
0000 - 0200
0800 - 1000
1600 - 1800
Measured System Noise
Note: All Spectra < 2 Fredericksburg Index
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Power Spectral Density $(nT)^2/Hz$
0.4
1.0
5
10
40
Frequency (Hz)

Figure 15

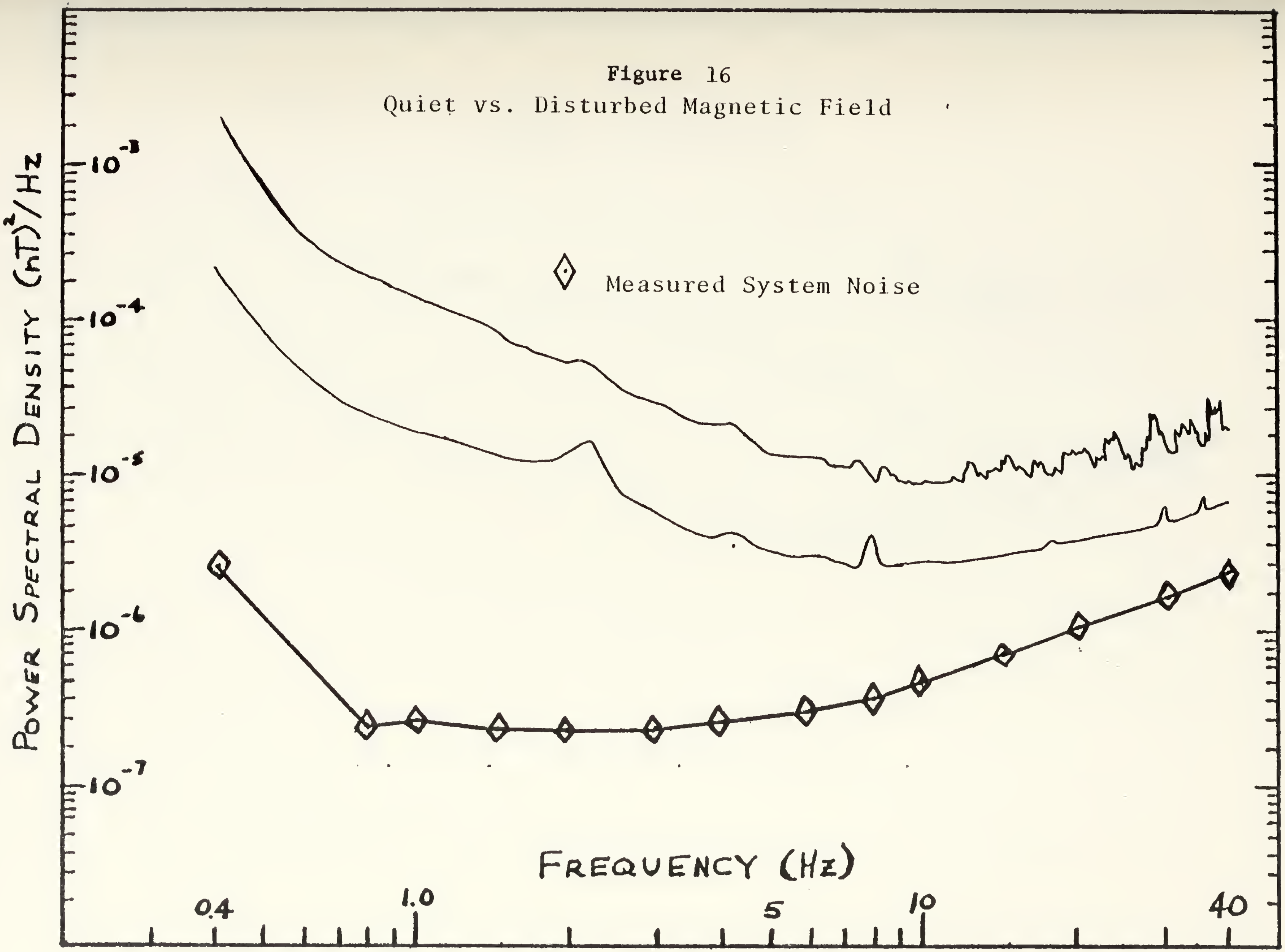
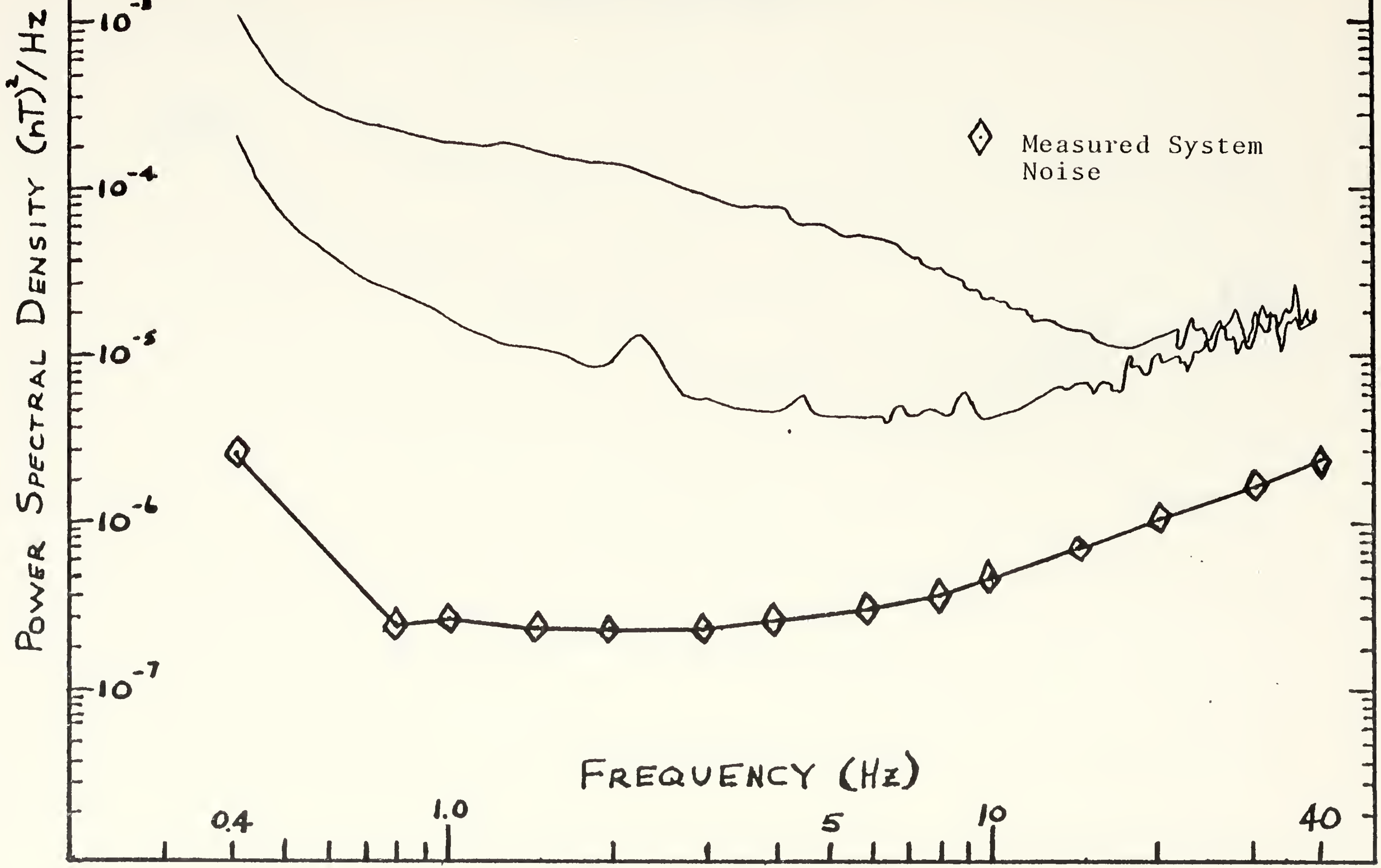


Figure 16
Quiet vs. Disturbed Magnetic Field

Figure 17

Magnetic Storm Maximum to Minimum Power Variations
(29 May - 1 June 1979)



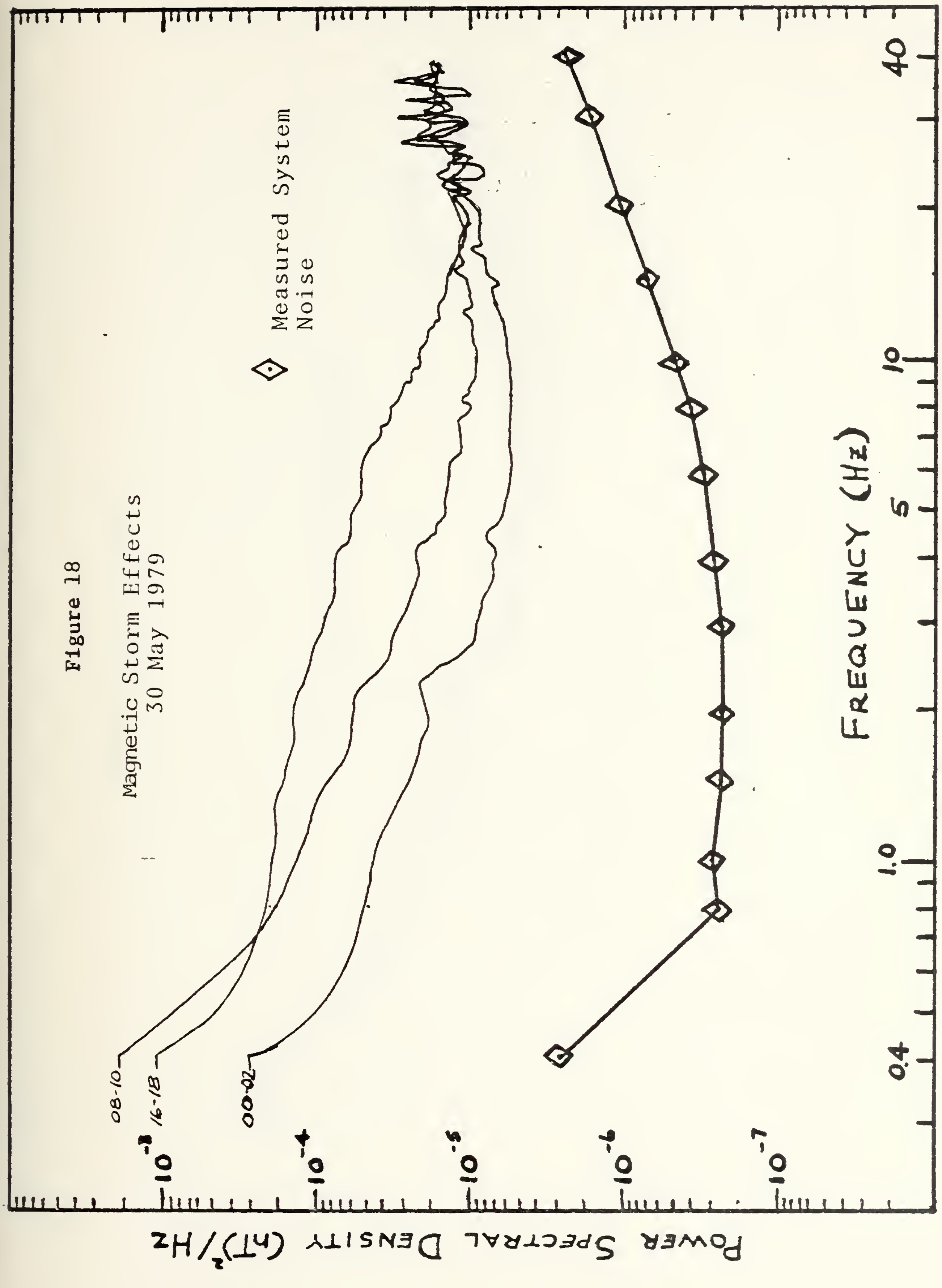


Figure 18

Magnetic Storm Effects
30 May 1979

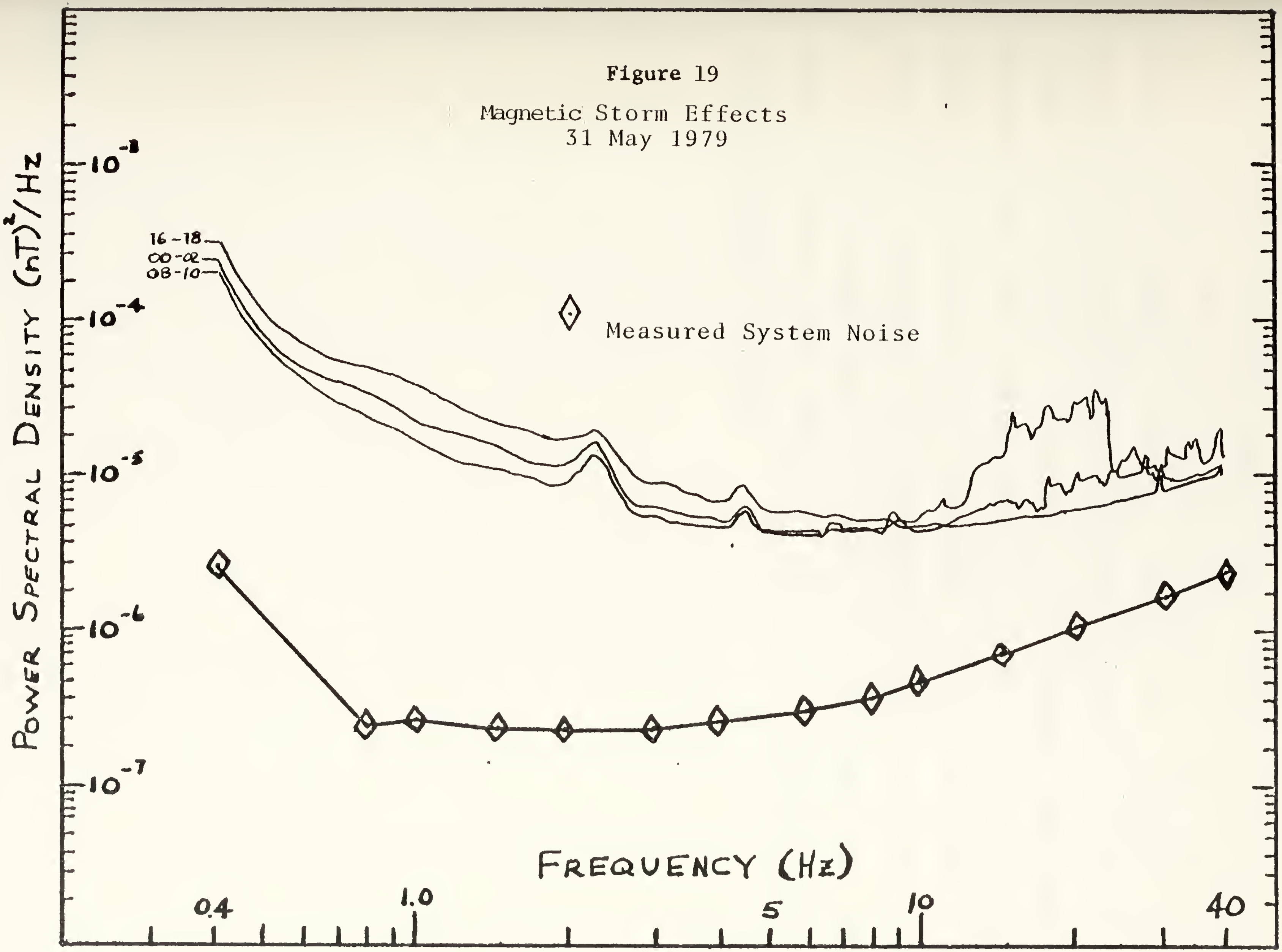


Figure 19

Magnetic Storm Effects
31 May 1979

each day. It is clear that the 30th was more active than the 31st with large increases (10 dB) in spectral density from 0.8 to 18 Hz. From 20 to 40 Hz the spectrum showed disturbances at all times of the day. The 31st was a quieter day magnetically, but exhibited extremely active high frequency components (from 12 to 24 Hz) at local midnight. At local morning (0800-1000), these oscillations were smaller and more spread out over the 20 to 40 Hz range. At the 1600-1800 time period the field was quiet throughout the frequency range.

The index numbers used for all of the above data were provided by the National Geophysical and Solar-Terestial Data Center, Boulder, Colorado.

VI. CONCLUSIONS

A. DISCUSSION

The general behavior of the observed spectra agrees with those illustrated in figure 1. Furthermore, the power spectral density at 1 Hz is close to that previously measured at Monterey [Barry, 1978] and by Smith and Buxton 1975 at Stanford. The average data had a power spectral density value of 2.6×10^{-5} $(nT)^2$/Hz. The average observed by Barry at 1 Hz was 8×10^{-5} $(nT)^2$/Hz. The Stanford average data indicates spectral density of 5×10^{-6} $(nT)^2$/Hz for the horizontal N-S component of the magnetic field. Figure 20 illustrates the above three average spectral densities at local midnight.

Both typical and average curves illustrate some interesting features. The composite average, figure 15, demonstrates that there is very little difference between the three time periods from 0.4 to 12 Hz for magnetically quiet days. From 12 to 40 Hz there is a small increase, ($\simeq$5 dB) due to the high frequency disturbances, in the 0000-0200 time frame. The small variations in spectral density of the composite averages are though to be due to the fact that the magnetic activity was extremely low during the short span of data collection (<2+ Index).

The typical spectra for the 0000-0200 shows a characteristic high activity level of narrow band components in the 20 to 40 Hz region. This activity was in the correct frequency region for "Sferic" type ELF activity. During periods of

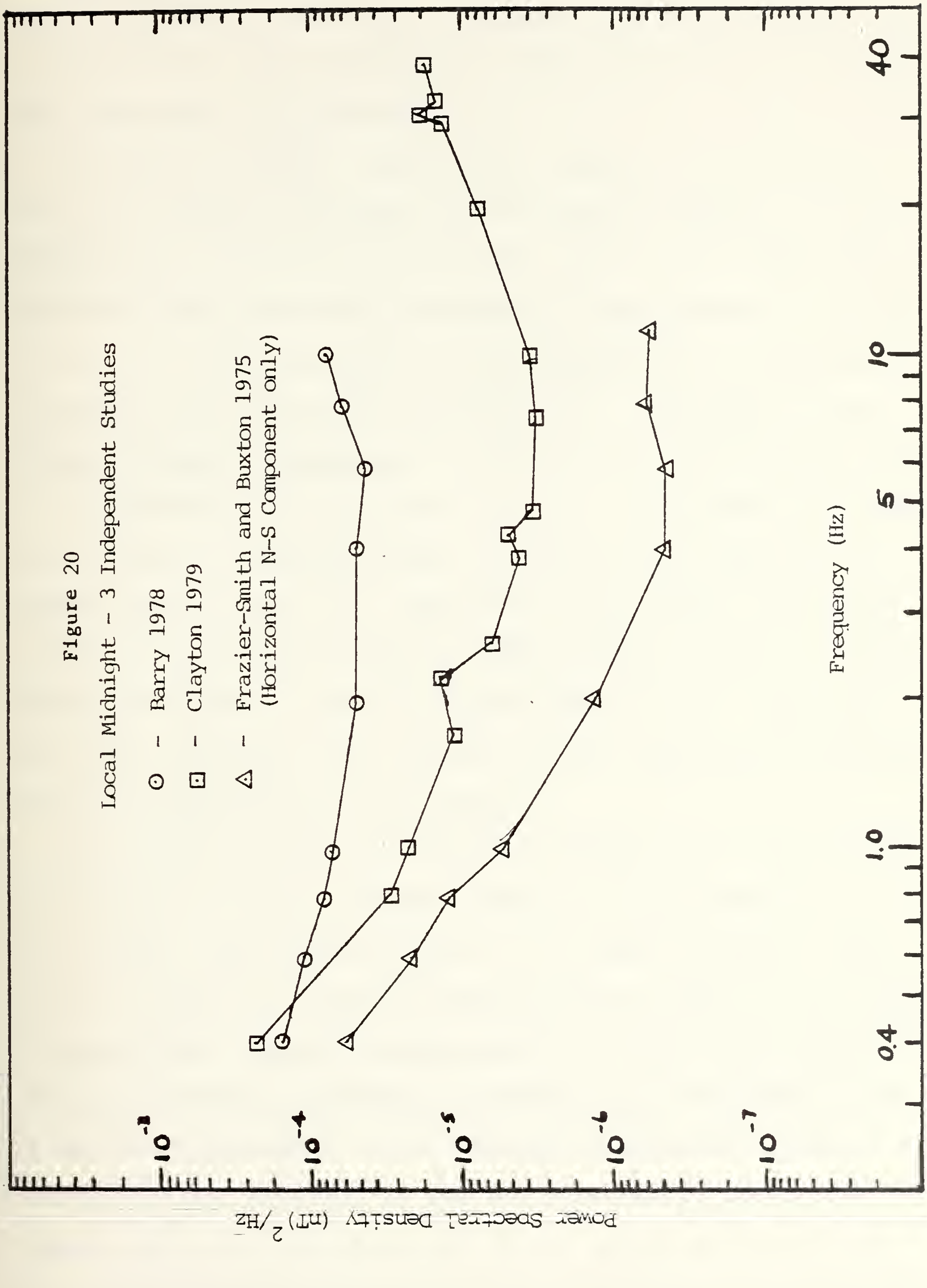


Figure 20

Local Midnight – 3 Independent Studies

higher magnetic activity, these characteristic disturbances would increase in magnitude. During the extremely quiet days this activity would subside to a negligible value as expected for ionospheric disturbances.

The local midnight, morning and afternoon spectra show that the maximum variations in the spectral density at low frequencies (1 Hz) are 10 to 20 dB, while at the upper frequencies these variations decrease to approximately 3 to 5 dB. This is in close agreement with the expected low and high frequency power density variations (ΔH) discussed in the Trapped Radiation Handbook [Claudis, Davidson and Newkirk 1971].

In general, the data shows a decline up to about 5 Hz where the Schumann resonances appear to flatten the curve up to approximately 12-15 Hz. Beyond that the curves rise slowly up to 40 Hz. This flattening effect was also noted by Frazier-Smith and Buxton to occur at approximately 5 Hz. However, the data collection time frames were not long enough to make a definite conclusion in this regard.

On all data curves, low frequency peaks at 2.2 and 4.4 Hz are evident. The 4.4 Hz peak appears to be a harmonic of the 2.2 Hz. The source of the 2.2 Hz peak is unknown, however, it has a high spectral density and is seen in all three time periods. Because it was seen in all the time periods, with approximately the same intensity, it is believed to be a man-made phenomena. It is possibly a function of the instrumentation, however, it was not observed in the system noise data.

Above 6 Hz, the natural activity is dominated by the "Schumann" resonances which have been recorded at approximately 8, 14, 20, 26 and 33 Hz. The spectra for local morning and afternoon clearly show a reoccurring frequency peak at 8 Hz. This is believed to be a first Schumann Resonance peak. There were other peaks observed at 20 and 33 Hz but they were less frequent and smaller in magnitude.

As noted above, the amount of data collected during this experiment was not adequate to draw general conclusions. A longer period of observation, extending throughout the year and for different levels of magnetic activity, is required to determine the full range of fluctuations in this band. It should also be noted that the magnetic variations in the 1 to 100 Hz frequency range are extremely small so that the cesium vapor magnetometer minimum sensitivity ($\approx .005$ nT) is very close to the signal under investigation. The system noise floor must be no greater than 1×10^{-6} $(nT)^2/Hz$, which is exactly where the data collection system used in this experiment operated.

B. RECOMMENDATIONS

This experiment was severely hindered by 60 Hz interference (Appendix A). In order to investigate the full 1 to 100 Hz frequency range the following recommendations are made to reduce system noise:

1) Design an amplifier and filter, compatible to the system, which is operated by DC power. The entire system can then be DC operated and the 60 Hz line interference

from equipment sources should be significantly reduced or eliminated.

2) A more sensitive sensor will be required to investigate frequency ranges above 100 Hz. The Varian 4938 magnetometer is very close to its limiting sensitivity (0.005 nT) in the frequency range investigated in this experiment, and the signal is known to fall off above 100 Hz. However, it can be concluded that the cesium vapor magnetometer, properly instrumented, is capable of measuring fluctuations in the geomagnetic field at the earth's surface from 0 to 40 Hz even on magnetically very quiet days.

APPENDIX A

VARIAN DATA COLLECTION SYSTEM REDESIGN SUMMARY

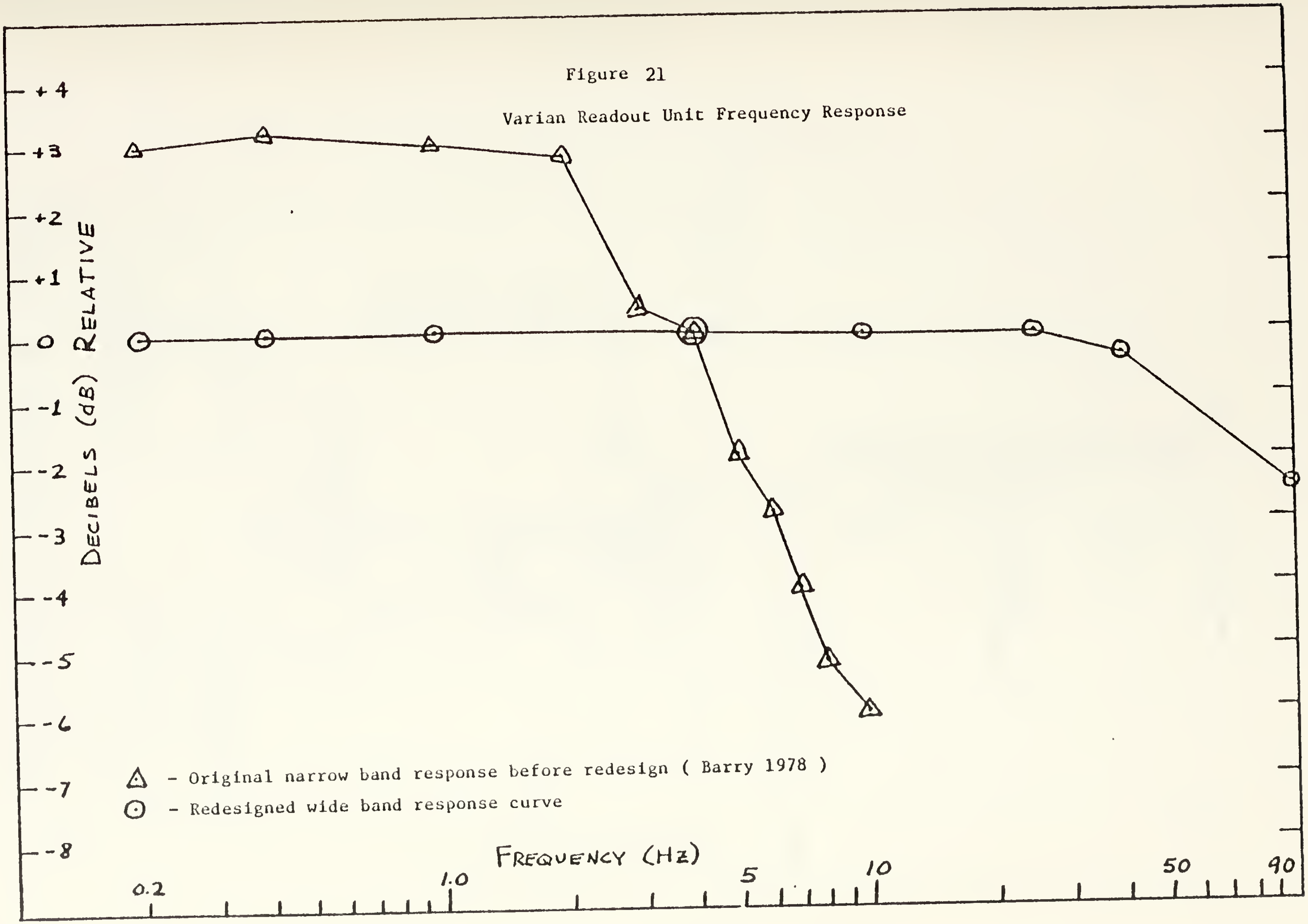
The system used during the first two thirds of this experiment was the Varian Model 4938 magnetometer and Readout Unit. This equipment had been used previously [Barry 1978] to measure power spectral densities in the 0.1 to 10 Hz frequency region but was subsequently proven to be too noisy to use at higher frequencies. The following discussion documents the design changes and procedures used to test the Varian system.

The previous measurements [Barry 1978] experienced signal degradation starting at approximately 2 Hz, with a 9 dB loss between 2 and 10 Hz. The Readout Unit output filter was found to be the limiting factor. The output filter was changed to include a wide band mode and a narrow band mode of operation. The narrow frequency band was exactly the same as the original system with an upper cutoff frequency of 2 Hz. The wide frequency mode had an upper cutoff frequency of approximately 100 Hz as shown in figure 21. It can be seen that the wide band mode of operation has excellent frequency response up to 100 Hz with a signal loss of less than 3 dB.

To determine the noise floor of the system it was configured as shown in figure 22 using a frequency synthesizer as a simulated sensor. The system noise curves of the Spectrum Analyzer, the differential amplifier, and the entire system are illustrated in figure 23. The entire system noise was essentially flat at 1×10^{-5} $(nT)^2/Hz$ over the 0.4-100 Hz

Figure 21

Varian Readout Unit Frequency Response



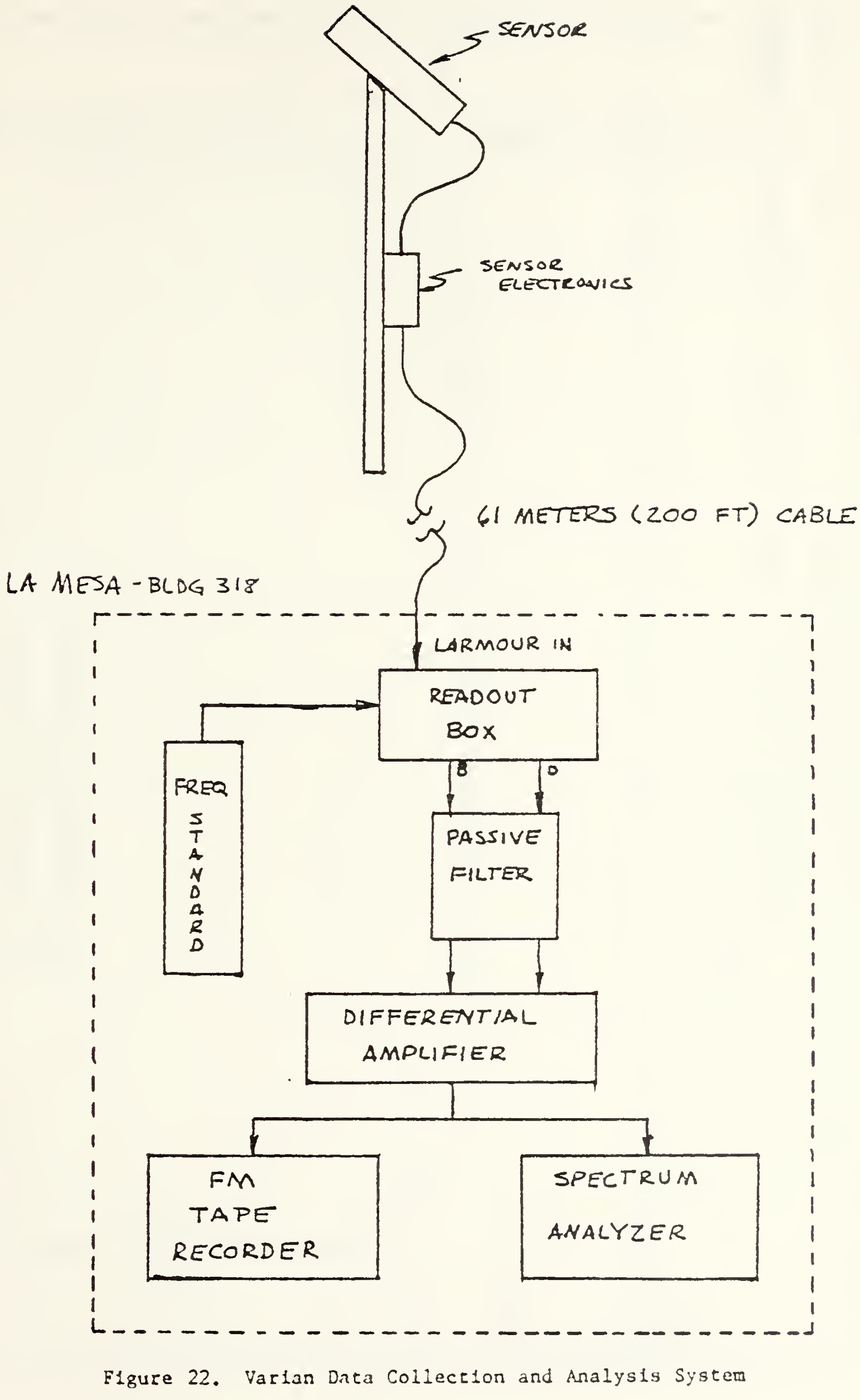


Figure 22. Varian Data Collection and Analysis System

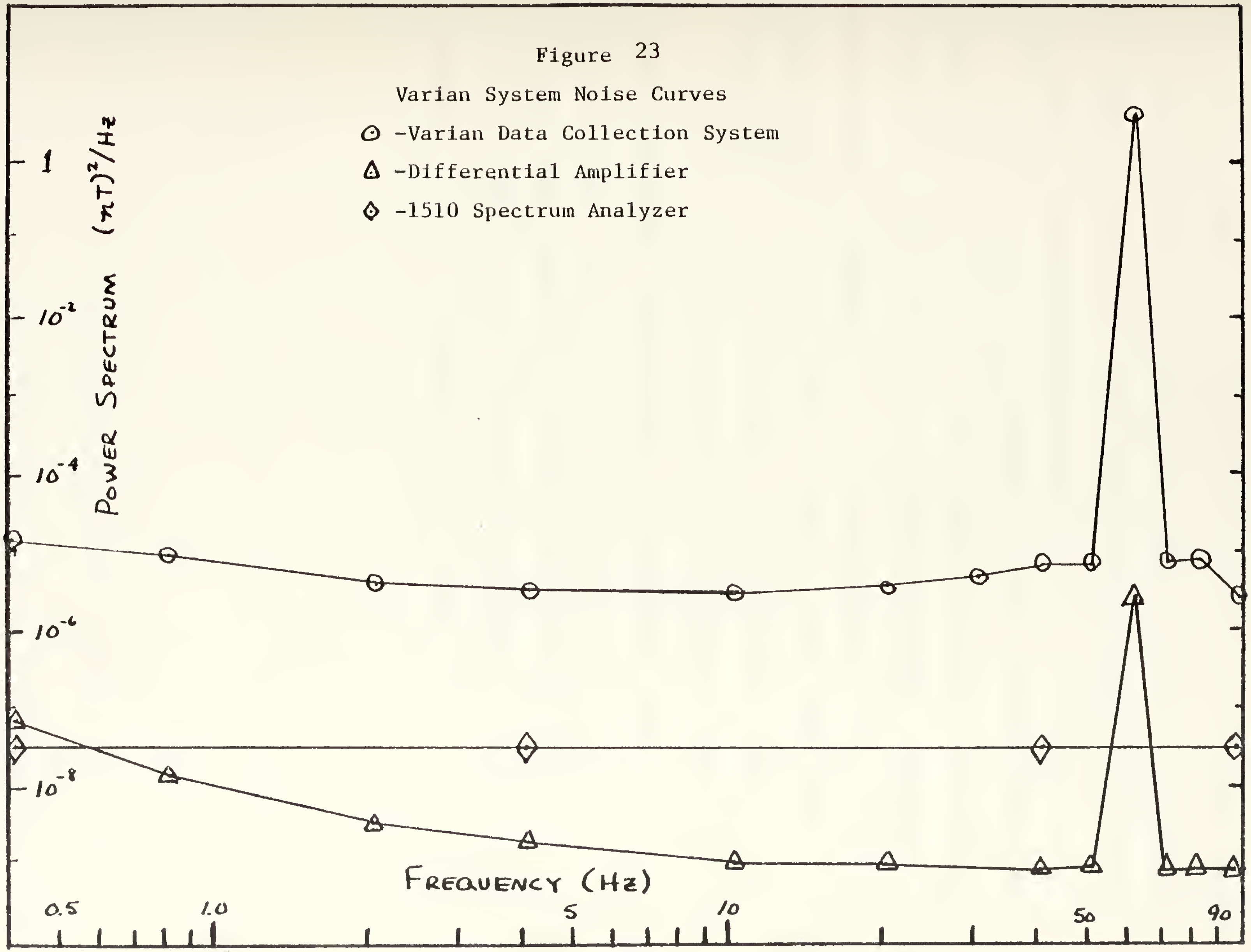


Figure 23

Varian System Noise Curves

region except for a +50 dB spike at 60 Hz, which exceeded the dynamic range of the tape recorder. The tape recorder also was the noisiest individual piece of equipment in the system. It was therefore, decided to do direct analysis of the data and tape in parallel. The signal levels expected in the 0.4 to 100 Hz range were approximately 10^{-4} $(nT)^2/Hz$ to 10^{-5} $(nT)^2/Hz$, and, the expected signal-to-noise ratio was about 5 to 10 dB. The actual signal-to-noise ratio was between 3 to 7 dB which was considered minimal. Several filters were tried to reduce the 60 Hz interference and allow for more amplification of the signal. However, the reduction in 60 Hz signal also reduced the signal into the noise above 30 Hz.

The change in the Readout Unit's output filter circuitry also changed the sensitivity of the discriminator output. The discriminator which converts a change in frequency to a D.C. voltage, was tested at different input frequencies. A system transfer function was established between 0.2 and 100 Hz. The sensitivity of the Readout Unit was found to be 8.25 mV/Hz.

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